MID-AMERICA TRANSPORTATION CENTER

Report # MATC-UNL: 421

Final Report
25-1121-0001-421

IntelliDrive Technology based Yellow Onset Decision Assistance System for Trucks

Anuj Sharma, Ph.D.
Assistant Professor
Department of Civil, Environmental, and Architectural Engineering
University of Nebraska-Lincoln

Nathaniel Burnett
Graduate Research Assistant
Sepideh S. Aria
Graduate Research Assistant

2012

A Cooperative Research Project sponsored by the U.S. Department of Transportation Research and Innovative Technology Administration

IntelliDrive Technology based Yellow Onset Decision Assistance System for Trucks

Anuj Sharma, Ph.D.
Assistant Professor
Department of Civil, Environmental, and Architectural Engineering
University of Nebraska–Lincoln

Nathaniel Burnett
Graduate Research Assistant
Department of Civil, Environmental, and Architectural Engineering
University of Nebraska–Lincoln

Sepideh S. Aria
Graduate Research Assistant
Department of Civil, Environmental, and Architectural Engineering
University of Nebraska–Lincoln

A Report on Research Sponsored by

Mid-America Transportation Center

University of Nebraska-Lincoln

July 2012

Technical Report Documentation Page

1. Report No. 25-1121-0001-421	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IntelliDrive Technology based Yellow Onset Decision Assistance System for Trucks		5. Report Date July 2012
		6. Performing Organization Code
7. Author(s) Anuj Sharma, Nathaniel Burnett, and Sepideh S. Aria		8. Performing Organization Report No. 25-1121-0001-421
9. Performing Organization Name and Address Mid-America Transportation Center 2200 Vine St. PO Box 830851 Lincoln, NE 68583-0851		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Research and Innovative Technology Administration 1200 New Jersey Ave., SE Washington, D.C. 20590		13. Type of Report and Period Covered August 2010-June 2012
		14. Sponsoring Agency Code MATC TRB RiP No. 28683
15. Supplementary Notes		

16. Abstract

Erroneous decisions by drivers to stop or go at the onset of yellow can lead to incidences of premature stopping or red light running, which in turn can cause severe rear end or right angle collisions. Because trucks or busses are relatively less maneuverable, and also have lower available acceleration rates, lower comfortable deceleration rates, and a higher line of sight than passenger vehicles, the risk of crashes is higher for trucks than other vehicles upon stop or go situations. Dilemma zone protection systems are used at high speed intersection s to enhance safety; however, such systems are generally designed around the dilemma zone boundaries of cars, and are static, lacking the intelligence to adapt to existing traffic, weather, or visibility conditions. The current research examined the effect of information systems such as advance warning flashers (AWFs) on the probability of conflict at onset yellow at high-speed intersections. A probit modeling technique was used to establish dilemma zone boundaries. Based on dilemma zone boundaries, probability of perceived conflict curves were computed and compared against actual conflicts that were observed at each of the studied intersections. This information was used to generate a better understanding of the risks associated with the use of AWFs. Results demonstrated that the provision of stop/go information that was consistent with the actual duration of yellow reduced the variability of driver decision making and reduced the dilemma hazard. When no information was provided to drivers, the critical time threshold for stopping was very close to the actual duration of yellow. These findings implied that drivers were inclined to stop when the time to stop bar was greater than the duration of yellow, and were inclined to go when the time to the stop bar was less than the duration of yellow. This concept was used to develop a prototype Yellow Onset Driver Assistance (YODA) system, consisting of a pole-mounted unit (StreetWave) and an in-vehicle unit (MobiWave). The in-vehicle unit was designed to request decision assistance from the pole-mounted unit as a truck approaches an intersection; based on the time to the stop bar and the duration of yellow, the YODA system advises drivers on whether or not it is safe to proceed through the intersection.

17. Key Words Dilemma zone protection, DSRC communication, Truck safety, high speed intersection	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 89	22. Price

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Mid-America Transportation Center (MATC)
Level of Service (LOS)
Advance Warning Flasher (AWF)
Wide Area Detector (WAD)
Intelligent Transportation System (ITS)
Coordinated Universal Time (UTC)
Greenwich Mean Time (GMT)

Acknowledgments

The research team would like to thank the Nebraska Department of Roads (especially Kent Wohlers, Bob Malquist, and Matt Neeman) and the City of Lincoln Public Works Department (especially Josh Meyers and Larry Jochum). We are grateful to Brad Giles from Wavetronix, who guided the setup of the detector data acquisition at the test sites and helped to generate custom codes for data collection. Thanks also go to the business team of the Mid-America Transportation Center (MATC), who contributed to this research by arranging transportation and providing technical support.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation’s University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Abstract

Erroneous decisions by drivers to stop or go at the onset of yellow can lead to incidences of premature stopping or red light running, which in turn can cause severe rear end or right angle collisions. Because trucks or busses are relatively less maneuverable, have lower available acceleration and lower comfortable deceleration rates, and have a higher line of sight than do passenger vehicles, the risk of crashes is higher for trucks than other vehicles upon stop or go situations. Dilemma zone protection systems are used at high speed intersection s to enhance safety; however, such systems are generally designed around the dilemma zone boundaries of cars, and are static, lacking the intelligence to adapt to existing traffic, weather, or visibility conditions. The current research examined the effect of information systems such as advance warning flashers (AWFs) on the probability of conflict at onset yellow at high-speed intersections. A probit modeling technique was used to establish dilemma zone boundaries. Based on dilemma zone boundaries, probability of perceived conflict curves were computed and compared against actual conflicts that were observed at each of the studied intersections. This information was used to generate a better understanding of the risks associated with the use of AWFs. Results demonstrated that the provision of stop/go information that was consistent with the actual duration of yellow reduced the variability of driver decision making and reduced the dilemma hazard. When no information was provided to drivers, the critical time threshold for stopping was very close to the actual duration of yellow. These findings implied that drivers were inclined to stop when the time to stop bar was greater than the duration of yellow, and were inclined to go when the time to the stop bar was less than the duration of yellow. This concept was used to develop a prototype Yellow Onset Driver Assistance (YODA) system, consisting of a pole-mounted unit (StreetWave) and an in-vehicle unit (MobiWave). The in-vehicle unit was

designed to request decision assistance from the pole-mounted unit as a truck approaches an intersection; based on the time to the stop bar and the duration of yellow, the YODA system advises drivers on whether or not it is safe to proceed through the intersection.

Chapter 1Introduction and Objectives

According to the National Highway Traffic Safety Administration (NHTSA), the total cost of motor vehicle collisions in the United States in 2006 was estimated at $230.6 billion (National Highway Traffic Safety Administration 2007). The total cost of motor vehicle collisions in the State of Nebraska was projected at $2.3 billion in 2007 (State of Nebraska 2007). Intersection or intersection-related crashes accounted for nearly 40.5% of all reported crashes in 2006 in the U.S (National Highway Traffic Safety Administration 2007).Every year, intersection and intersection-related crashes average approximately 8,500 fatal accidents, as shown in figure 1.1. In addition to the number of fatal crashes, approximately 900,000 injury crashes per year are intersection or intersection-related crashes.

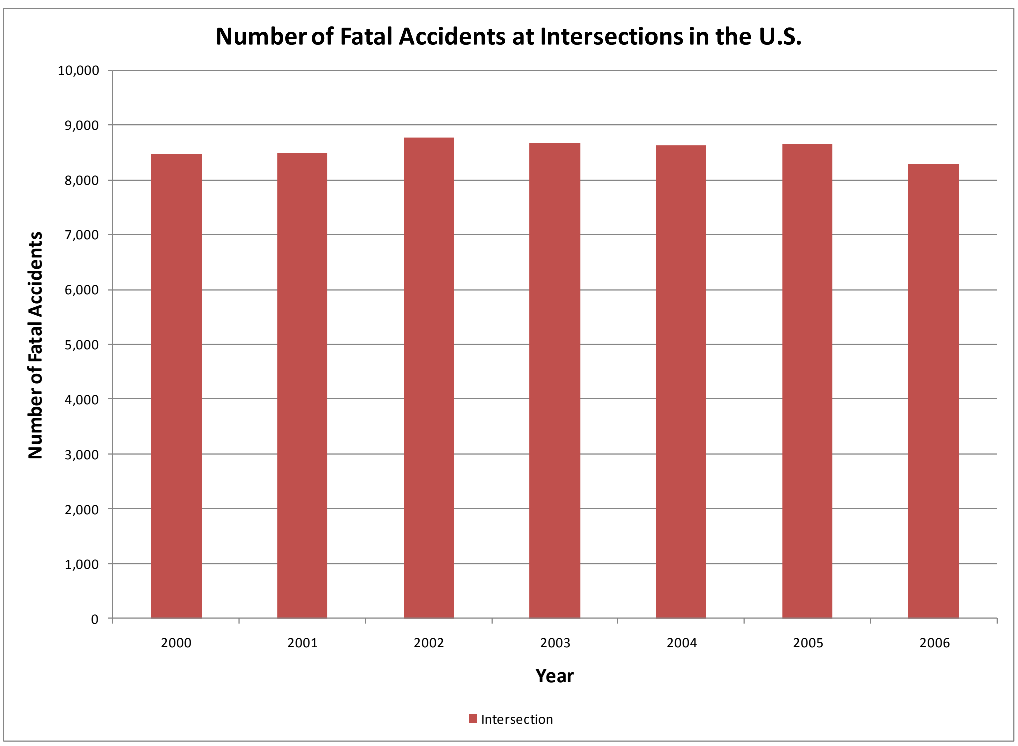


Figure 1.1 Intersection and intersection-related fatal accidents in the U.S.

The State of Nebraska is not void of this alarming overrepresentation of intersection and intersection-related crashes. Multi-vehicle accidents at intersections comprised 47.2% of all reported crashes in 2007 (State of Nebraska 2007). With the exception of 2001, the percentage of total crashes consisting of multi-vehicle collisions at intersections has remained constant in Nebraska for the past 10 years.

Each day at a typical intersection, approximately 700-800 occurrences of main-street phase terminations transpire in which drivers approaching an intersection at high speeds have to decide whether to proceed or stop at the onset of yellow (Sharma 2008). An incorrect decision could lead to a right angle or rear-end crash; these crashes account for roughly 80% of intersections crashes in Nebraska (State of Nebraska 2008).The zone where the risk of making an erroneous decision is high is termed the "dilemma zone" (Parsonson 1978).

The stop-or-go decision is even more difficult for heavy vehicles due to elevated constraints to their maneuverability. The NHTSA reports that a loaded tractor-trailer requires 20-40% farther to stop than a passenger car (Insurance Institute for Highway Safety 2006). In addition to the increased stopping distance required, trucks are less maneuverable. The State of Nebraska reported that in 2007, heavy trucks accounted for 13% of overall crashes and 3.4% of fatal crashes (State of Nebraska 2008). Although the number of passenger cars involved in fatal crashes in the United States has decreased since 1994, the number of large trucks involved in fatal crashes has remained relatively constant, at 5,000 per year (FARS 2008).

Specialized traffic signal control systems, often called *dilemma done protection systems*, are deployed at high speed intersections. There are two basic algorithms used by dilemma zone protection systems: the green extension algorithm and the green termination algorithm.

Dilemma zone protection offered at high-speed intersections is based on the dilemma zone for passenger vehicles. Federal law requires a passenger car's brakes to sustain a minimum deceleration rate of 21 ft/s^2. A truck's braking system is required to maintain a minimum deceleration rate of 14 ft/s.^{2} Therefore, at minimum deceleration rates, a truck requires 50% more stopping distance than a car (Federal Motor Carrier Safety Regulations 2005). Truck drivers may be more reluctant to stop at high-speed intersections because of the increased stopping distance or high deceleration rate required to stop. The extended amount of time required for trucks to achieve speed prior to stopping is another possible motivation for the reluctance to stop at such intersections.

Review of the literature confirms the deficiency of signal control strategies based specifically on measuring truck dilemma zone boundaries. Zimmerman (2007) explored the addition of an extended truck dilemma zone. Through the use of real-time simulation, Zimmerman concluded that an additional 1.5 s of upstream time added to the passenger car dilemma zone (i.e., 2.5 s-5.5 s from the stop line) would reduce the number of trucks in the dilemma zone. The current research found that the dilemma zone boundary for heavy vehicles (3 -8.2 s from the stop line) was almost twice the dilemma zone boundary of passenger vehicles (3.5-6 s from the stop line).

Even for passenger vehicles, the underlying concept of dilemma zone boundaries has a serious limitation. Although dilemma zone boundaries are determined using a sound stochastic concept, the definition of dilemma zone boundaries is still deterministic; a driver in the area where the probability of stopping ranges from 10%-90% is considered to be unsafe, and anyone outside of this area is considered to be safe. This binary approach states that a person is either at-risk or risk-free—no comments are made, however, about the level of risk at each location.

A new and improved surrogate measure dilemma zone hazard function was recently proposed by Sharma et al. (2007). This dilemma hazard function is a stochastic function estimating the probability of traffic conflict of varying severity levels at a specific spatial location.

Correct guidance for decisions at the onset of yellow can reduce the variability in driver decision making and improve the safety of the intersection. Currently, Advance Warning Flashers (AWF) represent the only driver assistance system in place. These systems are placed at a fixed distance from the stop bar and activate prior to the onset of yellow. Any vehicle in advance of the flashers is advised to stop, while any vehicle past the flashers can proceed through the intersection. The drawbacks of these flashers are as follows:

i) Advance flashers do not account for operational differences and dilemma zone differences occurring between different types of vehicles, providing, instead, the same information to both cars and trucks.

ii) Vehicles traveling at different speeds incur different crash risks, but are provided with the same information.

iii) The impact of weather and time of day is not accounted for by AWF.

iv) AWF does not consider the impact of the presence of other vehicles.

v) Personalized and dynamic information cannot be provided by AWF.

Using existing AWF systems as a test bed, the current research consisted of an in-depth study of the role of information on driver stop-go decisions. Based on the insights gained, a smart and dynamic yellow onset decision assist system was developed. This system was able to cater to individual vehicle assistance needs.

The Yellow Onset Driver Assistance (YODA) system consisted of a pole-mounted unit (street wave) and an in-vehicle unit. The in-vehicle unit requests decision assistance from the pole-mounted unit as a truck approaches an intersection. Based on vehicles' time to the stop bar and current speed, the pole-mounted unit responds to the in-vehicle unit with a recommended course of action. The system is a proof of concept for providing more personalized information to the drivers.

The current report is structured as follows: chapter 2 contains a literature review of past research pertaining to the development and advancement of dilemma zone definitions and methods of mitigation. Past and current methods for modeling driver behavior at high-speed intersections at the onset of yellow are presented, and the current practices involved in assessing the safety of vehicles approaching an intersection are reviewed. The limitations of these practices are explained.

Chapter 3 describes the six data collection sites that were utilized in the current research, five of which had AWF and one that did not have AWF. A combination of radar-based detectors and video was used to continuously track vehicles approaching high-speed signalized intersections. This chapter describes the different data collection setups and details the validation of each setup. In addition, the chapter discusses the steps taken to process the collected video.

Chapter 4 describes the theory underlying driver behavior upon approaching a signalized intersection. The decision process of drivers at the onset of yellow was modeled using the probit modeling technique. The impact of the role of information on driver decision making was assessed.

Chapter 5 details the development of the prototype YODA system. The utilized technology, codes, and testing of the prototype is described.

Chapter 6 summarizes study findings and proposes steps for future research. Overall, in regards to supplementing driver decision making at high speed intersection approaches, our findings prompt a new consideration for traffic engineers in terms of mitigating right-angle and rear-end crash risks

Chapter 2 Literature Review

2.1 Introduction

The following chapter contains a literature review on past research pertaining to the development and advancement of dilemma zone definitions and methods of risk mitigation. Past and current methods for modeling driver behavior at high-speed intersections at the onset of yellow are presented, as are current practices used in assessing the safety of vehicles approaching an intersection.

2.2 Dilemma Zone Definitions

There are two distinctive types of dilemma zones: *Type I* and *Type II*. Type I dilemma zones are caused by improper signal timing of the clearance intervals. Type II dilemma zones, referred to as “option,” or, “indecision” zones, are caused by variance in driver behavior. The following section will further describe the differences between the definitions of the two commonly proposed types of dilemma zones.

2.2.1 Type I Dilemma Zone

Gazis et.al. (1960) observed problems associated with drivers facing the yellow change interval; the authors defined the “amber light dilemma” as a situation in which a driver may be able to neither stop safely after the onset of yellow indication nor to clear an intersection before the signal turns red (Gazis et al. 1960). Figure 2.1 illustrates the concept of the Type I dilemma zone:

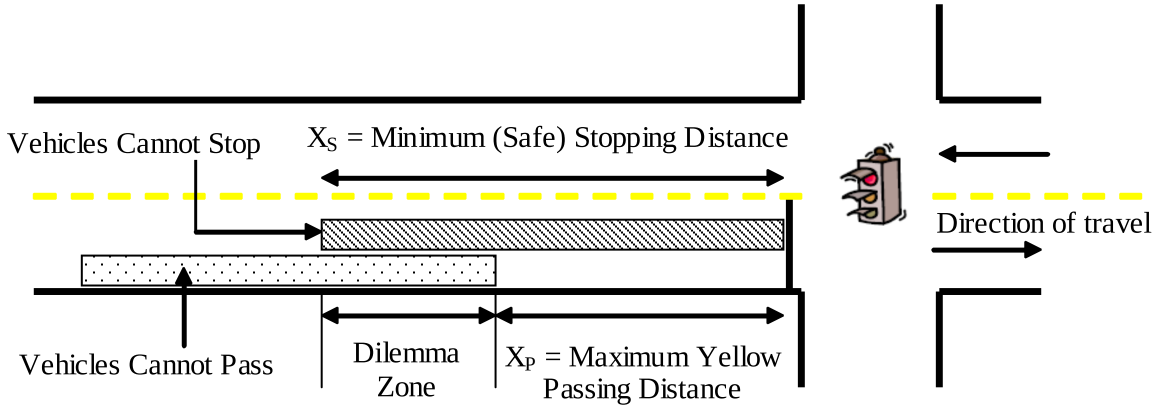


Figure 2.1 Illustration of Type I dilemma zone

The two critical distances shown in figure 2.1 are the maximum yellow passing distance (X_P) and the minimum safe stopping distance (X_S). A vehicle downstream of X_S will not be able to stop safely before the stop bar. Conversely, a vehicle upstream of X_P cannot safely advance upon and clear the intersection during the yellow phase. As shown in figure 2.1, when $X_S > X_P$, a vehicle located within the region between X_S and X_P can neither safely stop nor safely cross the intersection during the yellow phase, creating a "dilemma." Thus, the dilemma zone is the physical region between X_S and X_P when $X_S > X_P$. Equations 2.1 and 2.2 represent X_S and X_P.

$$X_S = V_0\delta_2 + \frac{V_0^2}{2a_2} \tag{2.1}$$

$$X_P = V_0\tau - W + \frac{1}{2}a_1(\tau - \delta_1)^2 \tag{2.2}$$

where,

X_S = minimum safe stopping distance (ft);

X_P = maximum yellow passing distance (ft);

V_0 = vehicle approach speed (ft/s);

δ_2 = driver's stopping perception-reaction time (s);

a_2 = driver's maximum comfortable deceleration rate (ft/s^2);

δ_1 = perception-reaction time of driver crossing the intersection (s);

a_1 = driver's maximum comfortable acceleration rate (ft/s^2);

τ = duration of yellow interval (s);

W = sum of intersection width and vehicle length (ft).

Equation 2.2 does not take into account an all-red clearance interval, which will be discussed later in this report. Therefore, with proper design of the yellow interval or a change in driver behavior, the Type I dilemma zone can be eliminated. In certain instances, drivers may eliminate the dilemma zone by accelerating to or above the speed limit. However, as Liu et al. (1996) mentioned, advising drivers to use the onset of yellow as an instruction to accelerate would be dangerous. Thus, assuming a crossing vehicle does not accelerate, the Type I dilemma zone may be eliminated by adjusting the yellow interval to set $X_S - X_P$ to 0.

$$\tau = \delta + \frac{v_0}{2a_2} + \frac{L+w}{v_0} \quad (2.3)$$

The yellow duration, τ, defined in the GHM model, has been divided into two intervals: the yellow permissive interval, $y = \delta + \frac{v_0}{2a_2}$, and the all-red clearance interval, $r = \frac{L+w}{v_0}$. Studies have shown a wide variability in driver behavior (Gazis et al. 1960; Olson and Rothery 1962; May 1968; Williams 1977; Parsonson and Santiago 1980; Sivak et al. 1982; Wortman and Matthias 1983; Chang et al. 1985; Liu et al. 2007). Olson and Rothery (1962) discovered that some drivers used the yellow interval as a green extension. May (1968) found that in an effort to avoid the dilemma zone some drivers accelerated or decelerated heavily. Figure 2.2 and table 2.1 illustrate the variability in perception reaction times and deceleration rates at the onset of yellow. The inability to consider variability in driver behavior variability in driver behavior is the main limitation of the GHM model.

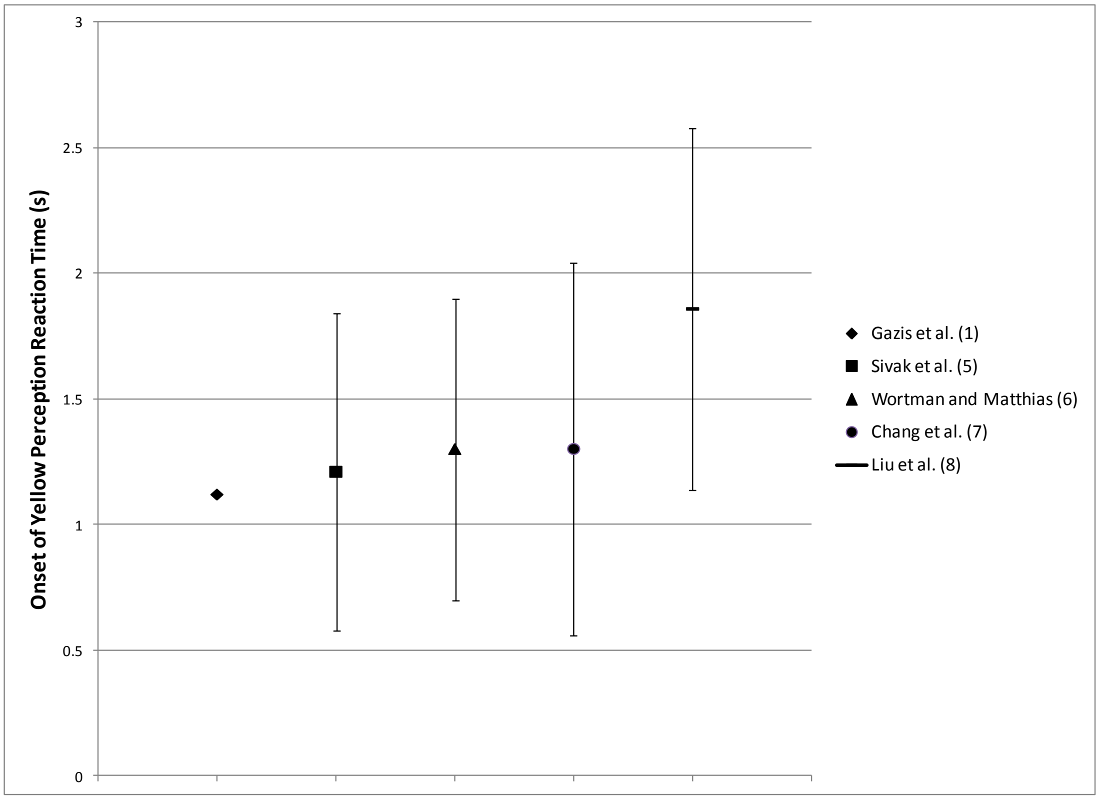


Figure 2.2 Previously reported perception reaction times

Table 2.1 Variability in previously reported deceleration rates

Author	Speeds studied/calculated	Mean deceleration rate (ft/s^2)
Gazis et.al. (1960)	45mph	16
Williams (1977)	10-25 mph	9.7
Parsonson and Santiago (1980)	-	10
Wortman and Matthias (1983)	30-50mph	11.5
Chang et.al (1985)	>20mph	9.2

2.2.2 Type II Dilemma Zone (Indecision Zone or Option Zone)

To account for variability in driver behavior, researchers defined a second type of dilemma zone. Also referred to as “indecision” or “option zone,” the Type II dilemma zone is based on a probabilistic approach to driver decision making at the onset of yellow. In this zone, drivers could either stop comfortably or clear the intersection before the end of yellow, thus resulting in the probabilistic nature of the zone. According to the literature search conducted for this report, ITE technical committee first documented Type II dilemma zones in a technical report by the Southern Section of ITE (ITE Technical Committee 1974). A driver on a high speed roadway encounters a dilemma on whether to stop or proceed through an intersection at the onset of yellow. As a result of the variability previously described, the Type II dilemma zone exists at the onset of every yellow indication. An incorrect decision to stop when it would have been safer to proceed can lead to a severe rear-end collision. Conversely, an incorrect decision to proceed through the intersection could lead to running a red light and a possibly causing a right angle collision. Figure 2.3 illustrates the Type II dilemma zone.

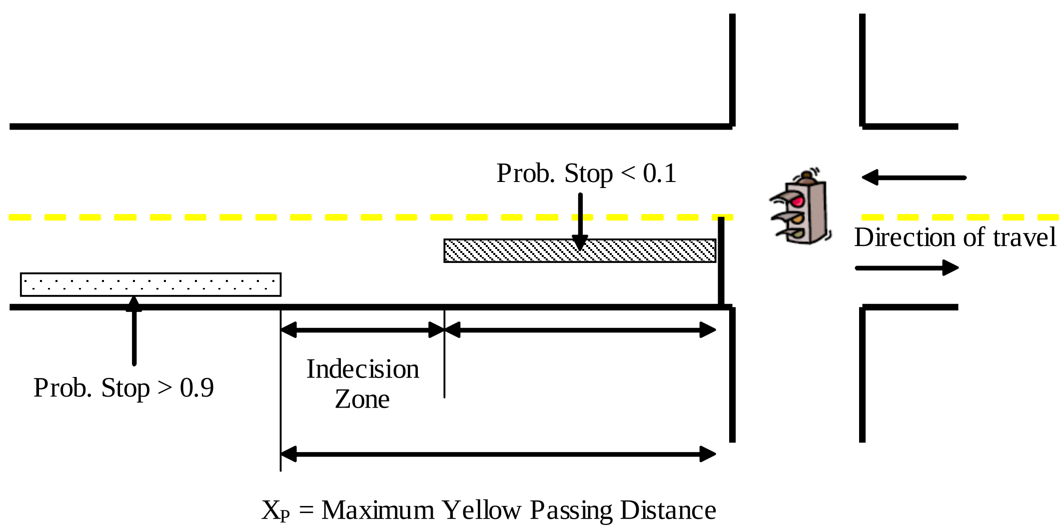


Figure 2.3 Illustration of Type II dilemma zone

Zeeger (1977) defined the type II dilemma zone as "…the road segment where more than 10 percent and less than 90 percent of the drivers would choose to stop." Researchers have attempted several different approaches to characterizing the indecision zone boundaries. Zeeger (1974) used a frequency-based approach to collect data on drivers' stopping decisions at specified distances and speeds in order to develop a cumulative distribution function. The dilemma zone boundaries were quantified as the distance and speed or time to the intersection.

At the onset of yellow, a driver can choose from two mutually exclusive courses of action: stop or go. The decision process can therefore be modeled by binary discrete choice models. Sheffi and Mahmassani (1981) modeled the driver decision process with a probit model to significantly reduce the sample size required for estimating dilemma zone boundaries. A driver's perceived time to reach the stop bar, T, randomly chosen from a population, was modeled as a random variable,

$$T = t + \xi \tag{2.4}$$

where,

t is the measured time to the stop bar at a constant speed;

the error term, ξ, designating the differences in driver's perception, is a random variable assumed to be normally distributed.

Sheffi and Mahmassani (1981) hypothesized that drivers would choose to proceed through the intersection if T was less than a critical value, T_{cr}. The critical time, T_{cr}, was also modeled as a normally distributed random variable accounting for a driver's experience, perception of acceleration rates, and aggressiveness:

$$T_{cr} = t_{cr} + \epsilon \tag{2.5}$$

where,

t_{cr}, is the mean critical time;

the error term, ϵ, is also normally distrusted across the driver population.

The probability of a random driver choosing to stop, P_{STOP} (T), is given by the probit equation:

$$P_{STOP}(T) = \Pr\{T_{cr} < T\} = \Phi\left(\frac{t - t_{cr}}{\sigma}\right) \tag{2.6}$$

where,

$\sigma = \sqrt{\sigma_{\xi}^{2} + \sigma_{\in}^{2} - 2\sigma_{\xi,\in}}$.

In comparison to the required 2,000 observations necessary to stabilize dilemma zone curves graphically (Mahmassani et.al. 1979), the previously described model was shown to stabilize at approximately 150 observations. Similar results for the stability of the probit model were demonstrated by Sharma et al. (2011)

Advantages of the model described above include the fact that dilemma zone curves are directly calculated from the model and a small sample size of only 150 observations is required to model dilemma zone curves

In addition to the probit model, dilemma zone boundaries have been estimated with other models, primarily the logit model. Similar to the probit model, the logit model is a binary discrete choice model. Recent studies using logit to develop probability of stopping curves include Bonneson and Son (2003), Gates et al. (2006), Papaioannou (2007), and Kim et al (2008). Rakha et al. (2007) used an empirical model to develop driver probability of stopping. Elmitiny et al. (2009) used tree-based classification to model the driver stop/go decisions. As a method of splitting data, classification trees are effective for segmenting the data into smaller and more homogeneous groups. Elmitiny et al.(2009) split the data based on distance to the intersection and speed at the onset of yellow; position of vehicle (leading or following); and vehicle type. Statistical comparisons can be made based directly on the various nodes defined by the researcher. For example, the same study revealed that drivers in the following position were more likely to make go decisions and run the red light than were drivers in the leading position, potentially exposing them to an increased risk of a rear-end crash.

Due to the dynamic nature of the decision dilemma zone, studies have examined variables contributing to driver decisions to stop or proceed through the intersection. Gates et al. (2006) observed that heavy vehicles had a higher probability than cars to proceed through the intersection. Similar results were observed by Wei et al (2009). Sharma (2011) proposed that the probability of stopping was a function of the acceleration required to cross the stop bar. Kim et al. (2008) proposed that yellow-onset speed, distance from the stop line, time to stopbar, and location of the signal head significantly affected driver stopping decisions. Figure 2.4 shows the variation in the dilemma zone boundaries based on previous findings for vehicles approaching an intersection at 50 mph.

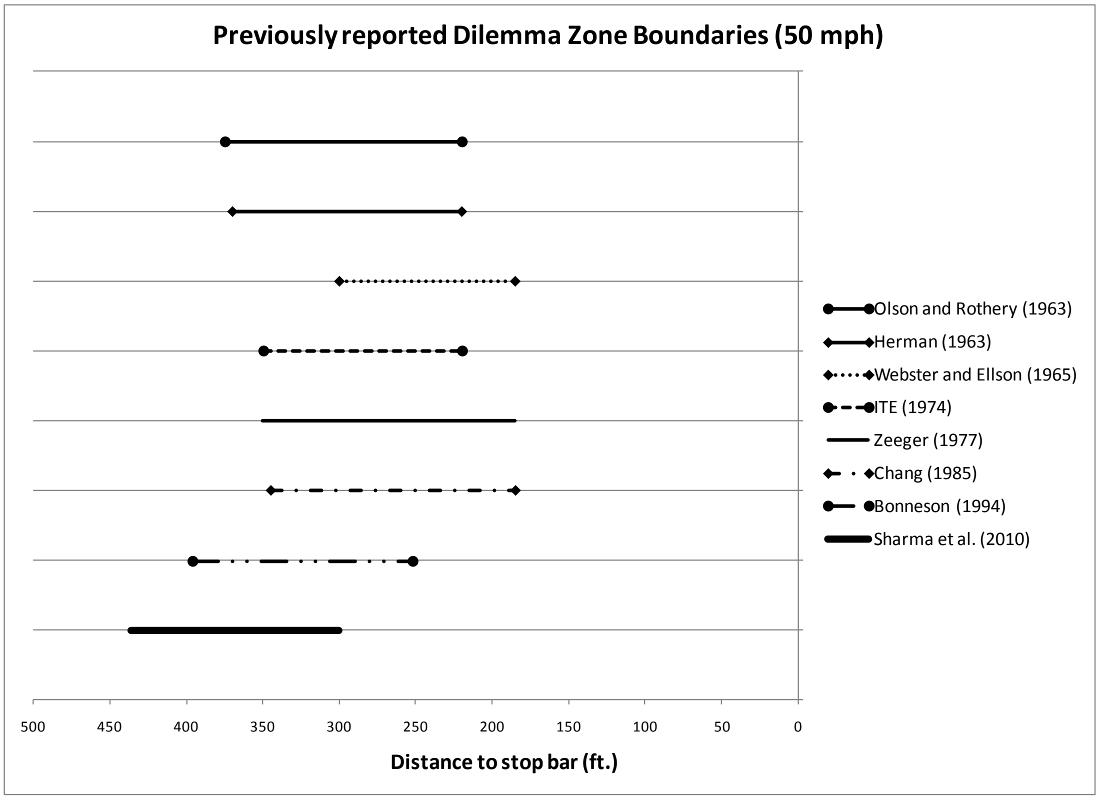


Figure 2.4 Dilemma zone boundaries (50 mph)

The statistical methods for calculating the traditional surrogate safety measure of the number of vehicles in the dilemma zone are sound; however, as implied by figure 2.4, the variations that occur in the defined boundaries are a result of the differences in dilemma zone definitions, types of drivers, and environmental and geometric layouts of the investigated sites. Site-specific dilemma zone boundaries are ideal for assessing crash risk, but this method of examining safety does not quantify the level of risk at different locations in the dilemma zone, since it describes drivers either as at-risk (in the dilemma zone) or free from risk (outside of the dilemma zone).

2.3 Effects of Yellow Length on Driver Behavior

Studies have also examined impact on driving behavior as a function of yellow interval duration. In his comparison study of intersections equipped versus not-equipped with flashing green, Knoflacher (1973) concluded that a decrease in right-angle crashes corresponded to increases in the duration of yellow. The effects of yellow interval duration on stopping have also been studied. Lengthy yellow intervals were found by Van der Horst and Wilmink (1986) to cause poor driving behavior for last-to-stop drivers at intersections. Instead of being presented with a red indication as they approached the stop line, drivers were stopping while the light was still yellow; the same drivers were inclined to proceed through the intersection the next time they approached it. Van der Horst and Wilmink (1986) found that drivers adjusted their stopping behavior as a function of longer change intervals. The probability of stopping for drivers 4 s from the intersection decreased from 0.5 for a yellow length of 3 s, to 0.34 for a yellow length of 5 s. Reductions in red light running (RLR) were found to decrease up to 50% for increases in yellow ranging from 0.5-1.5 s, as long as the yellow duration did not exceed 5.5 s. Koll et al. (2004) concluded that early stops should reduce the probability of right-angle collisions.

Contrary to the previous results, Olson and Rothery (1962) concluded that driver behavior did not change as a function of different yellow phase durations. Studies have also shown that overly-long amber can lead to greater variability in driver decision making, and could potentially increases rear-end conflicts (Olson and Rothery 1962; May 1968; Mahalel and Prashker 1987). Mahalel and Prashker (1987) noted a potential increase in the indecision zone for a lengthy “end-of-phase” warning interval. They observed an increase in the indecision zone with no flashing green from the normal zone of 2-5 s to a zone of 2-8 s for a 3 s yellow that was preceded by a 3 s flashing green; the authors presented evidence of an increased frequency of rear-end crashes due to the increase in the indecision zone.

2.4 Mitigation of Dilemma Zones

2.4.1 Green Extension

Advanced detection systems involve placing several loop detectors upstream of the intersection to detect approaching vehicles and extend the green. These detectors communicate with a computer that searches the signal controller to determine, based on vehicles' measured speeds, whether a green extension is required. Ideally, the green phase of the high speed approach is extended until there is no vehicle in the dilemma zone; however, a maximum green time is provided for this operation in order to avoid excessive delays to the cross street traffic. As long as they are discharging at saturation flow rate, all phases are allotted green, reducing delay. This is an all-or-nothing approach: dilemma zone protection is provided to the high speed vehicles prior to the maximum green time being reached, at which time the protection is removed. Developed to reduce the number of trucks being stopped at high speed rural intersections, the Texas Transportation Institute's (TTI) Truck Priority System is an example of a green extension system (1997). However, the system does not specifically provide dilemma zone protection. The system extends the phase by as much as 15 s past maximum green before reaching max-out, at which time dilemma zone protection is removed. Another example of a green extension system is Sweden's LHORVA system (1993).

2.4.2 Green Termination

Green termination algorithms are relatively new, and the systems implementing them exist at only a few intersections. These systems attempt to identify an appropriate time to end the green phase by predicting the value of a performance function for the near future. The objective is to minimize the performance function, which is based on the number of vehicles present in the dilemma zone and the length of the opposing queue. The application of these systems has been limited, and little quantitative data exists regarding the trade-off between efficiency, cost, and detector requirements.

2.4.3 D-CS

Texas Transportation Institute's Detection-Control System, or, D-CS, is a state-of-the-art system that has been implemented at eight intersections in Texas, U.S., and three in Ontario, Canada (2007). D-CS uses a green termination algorithm. The D-CS algorithm has two components: vehicle status and phase status. A speed trap sufficiently distant from the intersection (~ 800-1000 ft) is used to detect the speed and vehicle length of each vehicle. The projected arrival and departure time of each vehicle in its respective dilemma zone (based on speed and vehicle length) is used to maintain the "dilemma-zone matrix." This matrix is updated every 0.05 s. The phase status component uses the dilemma-zone matrix, maximum green time, and number of calls registered on opposing phases to control the end time for the main street green phase. The phase status is updated every 0.5 s.

Bonneson et al. (2005) observed reductions in the frequency of red-light violations at almost every approach at DC-S-equipped intersections. Overall, violations were reduced by 58%, with a reduction of about 80% for heavy vehicles. D-CS reduced violations 53% and 90% when replacing systems that used multiple advance loop detection and systems with no advance detection, respectively. On the approaches controlled by D-CS, severe crashes were reduced by 39%. Intersection operation improved at almost every approach at the five intersections studied. Reductions in control delay and stop frequency were 14 % and 9 %, respectively. Most likely, the reductions were due to D-CS's comparative operational efficiency relative to the previous detection and control strategies used at these intersections.

2.4.4 SOS – Self Optimizing Signal Control

Sweden's SOS system is another green termination algorithm designed for isolated intersections. Similar to D-CS, the system utilizes detectors in each lane to project the position of vehicles as they approach the intersection. The Miller algorithm calculates the cost of ending the green immediately or in t seconds (Kronborg 1997). Calculations are performed for different lengths of t, for example, 0.5 s up to 20 s. The algorithm evaluates three factors: reduction in delay and stops for vehicles using the green extension, increased delay and stops for opposing traffic, and increased delay and stops for vehicles that cannot use the green extension and have to wait for the next green period. In Kronborg (1997), the percentage of vehicles in the option zone was reduced by 38%. Additionally, the number of vehicles exposed to the risk of rear-end collision decreased by 58%.

2.4.5 Wavetronix SmartSensor Advance

Using digital wave radar, the Wavetronix SmartSensor Advance with SafeArrival technology is one of the newest vehicle detection based systems designed to improve dilemma zone protection (Smart Sensor Advance 2011). The system continuously tracks vehicle speed and range to estimate the time of arrival to the stop bar. SmartSensor Advance formulates the position and size of gaps in flowing traffic to adjust the physical location of gaps to extend the green time if necessary to provide safe passage. In a comparison study of dilemma zone protection systems, the Wavetronix system provided a greater reduction in the number of vehicles in the Type II dilemma zone than did inductive loops (Knodler 2009). The SmartSensor Advance decreased RLR incidents by more than 3 times the rate of the inductive loop system. SmartSensor advance shows potential for early detection of heavy vehicles; this property could be used to design different protection zones based on vehicle type.

2.4.6 Advance Warning

Placed upstream of high speed signalized intersections, AWF provides drivers with information regarding whether to prepare to stop at the upcoming traffic signal or to proceed through the intersection. Specifically, AWF is designed to minimize the number of vehicles trapped in their respective dilemma zones at the onset of yellow (Messer 2003). AWF have been found to improve dilemma zone protection in the state of Nebraska. McCoy and Pesti (2003) used advanced detection and AWF to develop an enhanced dilemma zone protection system. The system was found to reduce the number of max-outs, which result in reduced of dilemma zone protection. Gibby et al. (1992) concluded from an analysis of high-speed signalized intersections in California that AWF significantly reduced accident rates. Approaches having AWF displayed lower total, left-turn, right-angle, and rear-end accident rates. Sayed et al. (1999) calculated the reduction in total and severe accidents at intersections with AWF to be 10% and 12%, respectively.

2.4.6.1 Advanced warning's effects on RLR

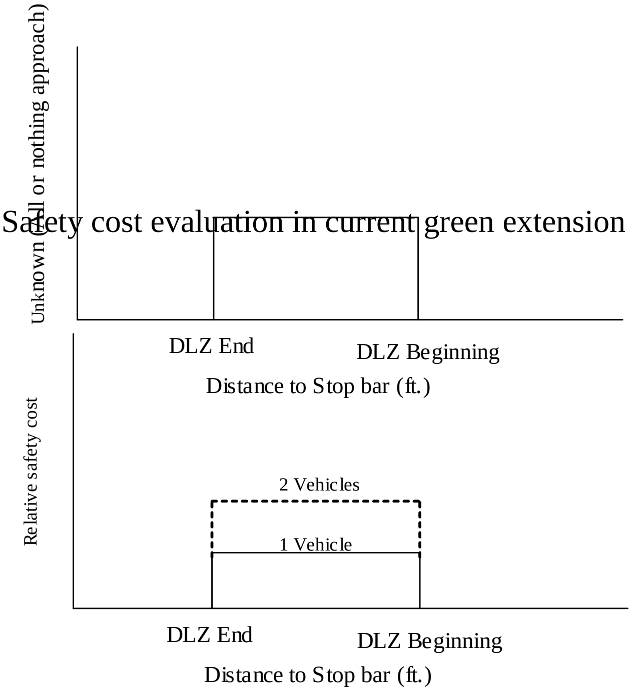
Farraher et al. (1999) observed red light running and vehicles speeds in Bloomington, Minnesota. Installation of AWF resulted in a 29% reduction in red light running, a 63% reduction in truck red light running, and an 18.2% reduction in the speed of red light running trucks. In addition, the TTI developed an Advanced Warning for End-of-Green System (AWEGS), which utilized a sign (text or symbolic), two amber flashers, and a pair of advanced inductive loops (Messer et al. 2003). The system, capable of identifying different classifications of vehicles (e.g. car, truck), has been found to decrease delay due to stoppages at traffic signals and provide extra dilemma zone protection for high-speed vehicles and trucks. Results showed a reduction in RLR by 38%-42% percent in the first 5 s of red.

Although the consensus surrounding AWF is that the system provides safety benefits, several concerns have also been raised. For example, Farraher et al. (1999) detected that drivers running red lights entered speeds above the speed limit, increasing the risk of crash for opposing traffic. Pant and Huang (1992) evaluated several high-speed intersections with AWF, detecting increases in vehicle speed as traffic signals approached the red phase; thus, the authors discouraged the use of Prepare to Stop When Flashing (PTSWF) and Flashing Symbolic Signal Ahead (FSSA) signs along tangent intersection approaches. Further testing performed by Pant and Xie (1995) at two intersections verified these findings.

Flashing green systems are similar to AWF systems, and have been implemented and tested thoroughly in Europe and Israel. Knoflacher (1973) studied decelerations and accidents at intersections equipped with and without flashing green systems, finding that intersections implemented with flashing green systems had higher deceleration rates and increases in the number of rear-end collisions. In a simulated study comparing driver responses at intersections with flashing green, Mahalel et al. (1985) noted a significant increase in erroneous decisions at the onset of yellow. In particular, inappropriate stop decisions at intersections with flashing green doubled to 77% in comparison to the 38% observed at intersections lacking the flashing green interval. This increase in inappropriate stops caused a considerable shift in the probability of stopping curves. Koll et al. (2004) compared the effects of flashing green on 10 approaches in Austria, Switzerland, and Germany. The examined safety impact was the amount of yellow and red stop line crossings observed. A substantial increase in the number of early stops was found in Austria. A larger option zone (an area where drivers could both proceed or stop safely) increased as a result.

2.5 Traffic Conflicts

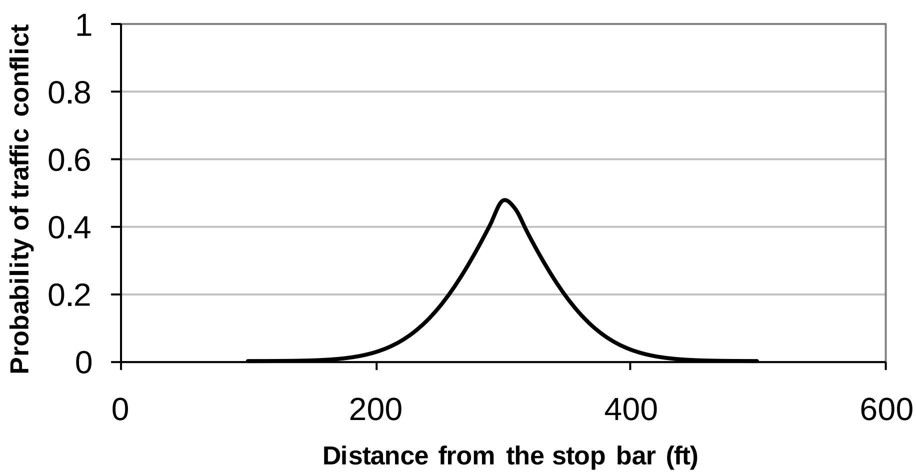
As previously mentioned, traditional surrogate measures of safety (such as the number of vehicles in the dilemma zone) fail to quantify the risk of a crash. Meanwhile, traffic conflicts have demonstrated usefulness as indirect measures with which to evaluate the safety of an intersection. Figures 2.6a to 2.6c contrast the present surrogate measure of safety with the proposed surrogate measure of safety. Widely used green extension systems are all-or-nothing approaches: all vehicles on the high-speed approaches are cleared until the maximum green time is reached, but at the end of the maximum green time, none of the vehicles on the high-speed approach are protected. As shown in figure 2.5a, these systems do not include a metric to measure the cost of the risk of crash. Green termination systems use the number of vehicles in the dilemma zone as a surrogate measure for quantifying the cost of risk. The number of vehicles is a rank-ordered metric, shown in figure 2.5b, where the cost of one vehicle in the dilemma zone is less than the cost of two vehicles in the dilemma zone; but the cost is independent of the positions of vehicles in the dilemma zone. Sharma (2011) modeled the dilemma zone hazard using the observed probability of stop and go at the onset of yellow. The probability of making an erroneous decision was used as the probability of traffic conflict. Dilemma hazard functions obtained for vehicles traveling at 45 mph, as estimated for the study site at Noblesville, IN, are shown in figure 2.5c. The probability of conflict curves developed by Sharma included single passenger vehicles only. The current research develops the dilemma hazard function for heavy vehicles. It should be noted that the dilemma hazard function can be further enhanced by adding severe conflict boundaries using acceleration and deceleration thresholds.



a) Safety cost evaluation in current green extension systems

b) Safety cost evaluation in advanced green termination systems

Figure 2.5 Comparison of traditional and proposed surrogate methods of safety



c) Proposed evaluation of safety cost

Figure 2.5 (cont'd.) Comparison of traditional and proposed surrogate methods of safety

2.5.1 Traffic Conflict Technique

Over the past four decades, the traffic conflict technique (TCT) has evolved, demonstrating its usefulness for indirectly evaluating the safety of intersections. The technique originated from research performed at the General Motors laboratory in Detroit, MI, being used to identify safety problems relating to vehicle construction. Perkins and Harris (1968) defined a conflict as “The occurrence of evasive actions, such as braking or weaving, which are forced on the driver by an impending crash situation or a traffic violation;” they categorized the conflicts into left-turn conflicts, cross-traffic conflicts, weave conflicts, and rear-end conflicts.

TCT gained popularity as research efforts attempted to establish a direct relationship between conflicts and crashes (Baker 1972; Spicer 1972; Cooper 1973; Paddock 1974). Research has made clear that conflict data is a much faster method of data collection than waiting for an actual crash history to develop; for this reason, conflict data, as opposed to crash data, allows researcher to make a determination regarding the safety of a specific intersection rather rapidly. This allows for information regarding the safety of an intersection to be collected rather quickly. Cooper and Ferguson (1976) calculated the ratio of the rate of serious conflicts to the rate of crashes, deriving a figure of approximately 2,000:1. A recent study by the FHWA (2008) found the ratio of traffic conflicts to actual crashes to be approximately 20,000:1. In addition to more rapid data collection, TCT facilitates the quick identification of the safety deficiencies at intersections. Thus, TCT allows traffic engineers the opportunity to provide proactive safety improvements at intersections instead of waiting for crash histories to evolve.

Questions regarding TCT have been raised by several researchers. Glennon et al. (1977) expressed concern over the use of the TCT technique, stating that the reliability of TCT for estimating crash potential is questionable. The same authors found that for every study in favor of TCT, there was a study that opposed it; they argued that the ability to predict the number of crashes at an intersection was extremely improbable given that conflicts and crashes are random events.

Although concerns have been raised regarding the use of TCT, recent studies have continued to advocate its use as a surrogate measure of safety. Glauz et al. (1985) investigated two types of expected crash prediction rates, one based on conflict ratios and the other based on crash histories. The study determined the difference to be statistically insignificant; thus, an estimate of the expected crash rates using traffic conflicts can be as accurate and precise as an estimate predicted by crash history. Hyden (1987) concluded that conflicts and crashes did in fact share the same severity distribution based on time-to-accident (TA) and speed values. The use of traffic conflict as a surrogate measure for traffic safety in micro-simulation has been advocated by Fazio et al. (1993), and by Gettman and Head (2003), who performed a detailed use-case analysis.

2.5.2 Traffic Conflicts at the Onset of Yellow

Zeeger (1977) identified six conflicts that can occur at the onset of yellow. The following definitions of the six conflicts were used during the conflict analysis performed as part of this report:

- Red light runner (RLR): A red light violation was defined as occurring when the front of the vehicle was behind the stop line at the onset of red.
- Abrupt stop: An abrupt stop occurs when a vehicle could successfully clear the intersection but decides to stop. Abrupt stop conflicts can be viewed visually and calculated mathematically based on the onset of yellow distance and speed.

- Swerve-to-avoid collision: Classified as an erratic maneuver that occurs when a driver swerves out of their lane to avoid hitting the vehicle stopped at the light in front of them.
- Vehicle skidded: This is a more severe case of an abrupt stop where the vehicle's wheels "lock-up" in order to stop. This conflict can be heard audibly.
- Acceleration through yellow: Acceleration through yellow is identified either by being heard audibly or through mathematical calculation. Each vehicle's distance is projected at the onset of red based on the onset of yellow distance and vehicle speed, assuming constant speed. Acceleration through yellow conflict is assigned if the vehicle successfully crosses the stop bar but would not have done so if based on the constant speed projection.
- Brakes applied before passing through: This conflict can be viewed visually when, at the onset of yellow, the driver applied the brakes before passing through the intersection. It indicates the indecisiveness of drivers when approaching the intersection.

2.6 Dilemma Zone Hazard Models

Recently, studies have quantified the level of risk associated with being in the dilemma zone by developing dilemma hazard models. The recently developed dilemma hazard is a new and potential measure of traffic conflict. Li (2009) validated and calibrated the dilemma hazard model based on an approach developed by the American Society of Civil Engineers (ASCE). In order to calculate the dilemma hazard, the dilemma hazard model compares driver decisions and actual driving capability as a function of Time-to-Intersection (TTI) at the onset of yellow. The approach uses driver decisions at the onset of yellow, their actual capabilities based on vehicle kinematics, and previously reported acceleration and deceleration rates. The collected data was simulated using Monte Carlo simulation to establish dilemma hazard values within the dilemma zone boundaries of 2-5 s (Li 2009). Models were created for single vehicle and multiple (two) vehicle scenarios. Results of the simulation, shown in figure 2.6, illustrate the effect of signal timings on the dilemma hazard.

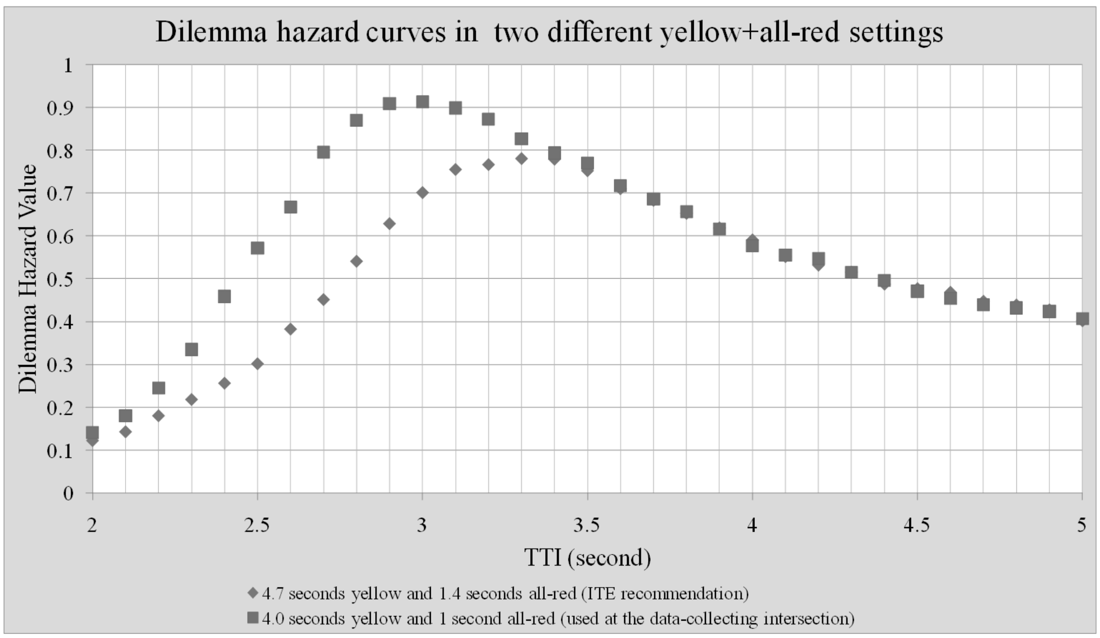


Figure 2.6 Dilemma hazard curves for various yellow and all-red clearance intervals (Li 2009)

Sharma et al. (2011) provided theoretical justification for using the probability of stopping to estimate the probability of conflict for single vehicles at high-speed intersections. A detailed discussion of this topic is provided in the following chapter.

2.7 Summary

The development of knowledge regarding dilemma zones and traffic conflicts has continuously progressed. The traditional surrogate measure of safety—the dilemma zone—denotes the region of risk, but does not quantify the level of risk. Recently, the dilemma hazard model and dilemma hazard function have attempted to quantify the level of risk associated with being in the dilemma zone at the onset of yellow. The current study aimed to identify the impact of providing additional information on driver stop and go decision making. The insights gained were used to develop the prototype YODA system.

Chapter 3 Data Collection

3.1 Introduction

To achieve as thorough an analysis as possible, five locations were selected for data collection, and a sixth site was evaluated for comparison. A combination of radar based detectors and video was used to continuously track vehicles approaching high-speed signalized intersections. This chapter describes the data collection locations, equipment setup and calibration, and video processing tasks.

3.2 Data Collection Sites

This section describes the six studied intersections:

3.2.1 US 77 and Saltillo Rd.

The first intersection studied was the northbound approach of US 77 and Saltillo Rd. Located east of Lincoln, Nebraska, US Highway 77 runs north and south. The intersection has two through lanes and both a left and right turn lane. Two PTSWF flashers are positioned on both sides of US 77, 650 ft. from the stop bar. The speed limit is 65 mph until approximately 1,150 ft. before the intersection, when the speed limit changes to 55 mph.

3.2.2 Highway 2 and 84th St.

The second intersection was the high-speed signalized intersection of Highway 2 and 84th St. in Lincoln, Nebraska. Highway 2 is a major thoroughfare in Lincoln, particularly for heavy vehicles. The percentage of heavy vehicles at the studied intersection was 10%**.** The eastbound approach of Highway 2 has two through lanes, two left turn lanes, and a right turn lane. Two PTSWF signs, along with flashers, are positioned on both sides of Highway 2, 563 ft. from the stop bar. Figure 3.1 shows what a driver approaching the intersection sees.

Figure 3.1 View of advance warning flashers prior to intersection

3.2.3 US 77 and Pioneers

US 77 and Pioneers Blvd., located five miles north of US 77 and Saltillo, was the third intersection studied. The southbound approach of US 77 and Pioneers has two through lanes and one left turn lane. Two PTSWF flashers are positioned on both sides of US 77, 650 ft. from the stop bar. The speed limit is 55 mph along this stretch of US 77.

3.2.4 Highway 34 and N79

The last intersection studied in Lincoln was the westbound approach of Highway 34 and N 79. This intersection is northwest of Lincoln, with a speed limit of 60 mph. With no left turn lane and a turnoff for vehicles desiring to travel north prior to the intersection, the westbound approach has only two through lanes. In addition, the intersection is equipped with two PTSWF flashers, 650 ft. from the stop bar.

3.2.5 Highway 75 and Platteview Rd.

Shown in figure 3.2 US 75 and Platteview Road, is located south of Bellevue, Nebraska. The southbound approach of US 75 and Platteview has two through lanes and both a right and left turn lane. Two PTWSF flashers are positioned on both sides of US 75, 438 ft. from the stop bar. Approximately 1,550 ft. upstream of the intersection, the speed limit changes from 60 mph to 55 mph.

3.2.6 SR32 and SR 37

The last site used for data analysis was the signalized intersection of SR 37 and SR 32 at Noblesville, Indiana. The southbound approach of SR 37 has two through lanes and both a right and left turn lane. The speed limit of SR 37 is 55 mph. Unlike the other five sites, this intersection does not have advance warning flashers. In addition, the wide area detectors (WAD) and camera were mounted on the mast arm, contrasting the previous locations that were on the side of the road.

Table 3.1 presents some important site characteristics. Figure 3.2 presents aerial photographs of each site.

Table 3.1 Detailed site characteristics

	Saltillo	Highway 2	Pioneers	US 34	US 75	SR 37
Site Code	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Yellow phase	4.4 s	5.6 s	4.9 s	4.4 s	4.5 s	5.0 s
Mean speed	54.1	48.5	52.8	56.6	51.4	46.6
Posted speed limit	55 mph	55 mph	55 mph	60 mph	55 mph	55 mph
85th Percentile speed	64	55	58.3	63	61	55
Use of AWF	Yes	Yes	Yes	Yes	Yes	No
AWF Distance	650 ft.	563 ft.	650 ft.	650 ft.	470 ft	-
AWF Time before yellow	7.0 s	8.0 s	8.0 s	7.0 s	6.0 s	-

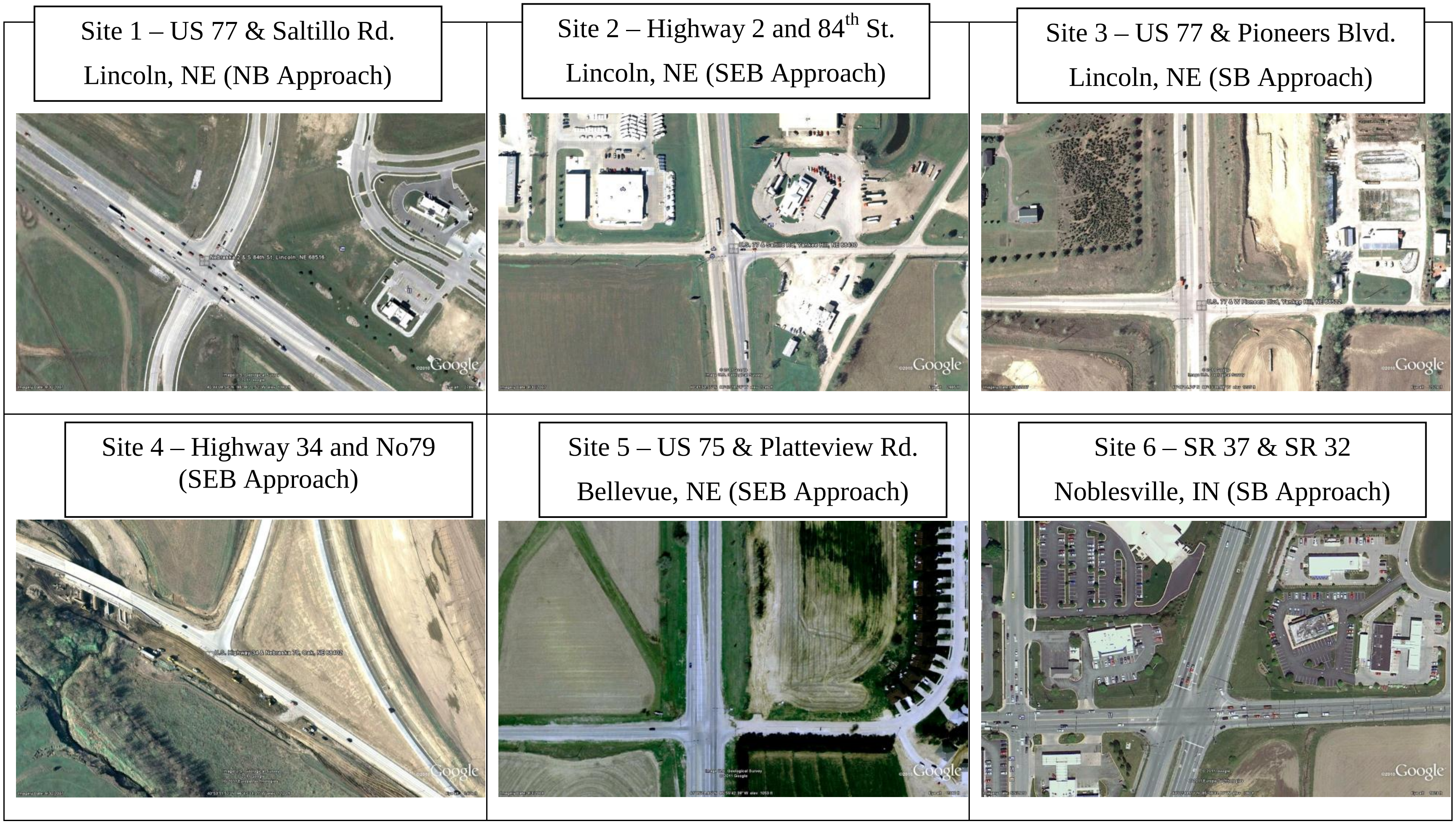


Figure 3.2 Aerial views of data collection sites

3.3 Data Collection

In order to maintain consistency during the collection period, data was collected only during good weather days. A variety of traffic conditions were examined by collecting data during both peak and off-peak hours. A summary of the dates and times of data collection at each site is shown in tables 3.2 and 3.3. Data was collected at six intersections using three different setups. This section will discuss the three different equipment setups and the calibration of each setup.

Table 3.2 Summary of data collected at AWF locations

Site Location	Day Collected	Hours Collected
Highway 2 and 84th St., Lincoln (Eastbound)	July-07-2010	10:30 AM - 12:30 PM; 1:00 PM - 3:00 PM
	July-09-2010	10:30 AM - 12:30 PM; 1:00 PM - 3:00 PM
	July-15-2010	10:30 AM - 12:0 PM; 1:00 PM - 3:00 PM
	July-16-2010	10:30 AM - 12:30 PM
	July-19-2010	1:00 PM - 3:00 PM
	July-20-2010	1:00 PM - 1:45 PM; 2:45 PM - 3:00 PM
	November-08-2010	10:45 AM - 5:00 PM
	November-15-2010	3:30 PM - 4:45 PM
	November-16-2010	1:30 PM - 3:00 PM
	November-17-2010	2:30 PM - 4:00 PM
	November-22-2010	1:45 PM - 4:00 PM
	November-23-2010	1:45 PM - 4:00 PM
US-77 & Saltillo Rd., Lincoln (Northbound)	September-29-2010	8:00 AM - 4:00 PM
	September-30-2010	10:45 AM - 6:00 PM
US-77 & Pioneers Blvd., Lincoln (Southbound)	October-13-2010	8:00 AM - 4:00 PM
	October-14-2010	8:00 AM - 4:00 PM
US-34 & N-79, Lincoln (Westbound)	October-20-2010	8:00 AM - 4:00 PM
	October-21-2010	8:00 AM - 4:00 PM
	November-23-2010	11:00 AM - 4:15 PM
US-75 & Platteview Rd., Bellevue (Southbound)	November-18-2010	8:00 AM - 3:00 PM
	November-19-2010	9:00 AM - 4:00 PM

Table 3.3 Summary of data collection at Noblesville

Site Location	Day Collected	Hours Collected
SR37 and SR32, Noblesville (Southbound)	September-12-2007	6:00 AM - 9:00 AM
	September-20-2007	6:00 AM - 7:00 AM
	September-28-2007	6:00 AM - 12:30 PM & 6:00 PM - 8:00 PM
	October-02-2007	6:00 AM - 10:00 AM
	October-03-2007	1:00 PM - 4:00 PM & 6:00 PM - 8:00 PM
	October-05-2007	9:00 AM - 11:00 AM & 7:00 PM - 8:00 PM
	October-09-2007	3:00 PM - 4:00 PM & 6:00 PM - 8:00 PM
	October-12-2007	3:00 PM - 8:00 PM
	October-29-2007	6:00 PM - 8:00 PM
	October-30-2007	6:00 AM - 10:00 AM & 7:00 PM - 8:00 PM
	November-01-2007	6:00 AM - 12:00 PM & 6:00 PM - 8:00 PM
	November-02-2007	6:00 AM - 11:00 AM &3:00 PM - 5:00 PM
	November-09-2007	8:00 AM - 11:00 AM
	November-27-2007	7:00 PM - 8:00 PM
	February-28-2008	6:00 AM - 6:00 PM
	March-11-2008	9:00 AM - 2:00 PM
	March-12-2008	12:00 PM - 7:00 PM
	March-23-2008	10:00 AM - 8:00 PM
	March-24-2008	8:00 AM - 12:00 PM
	April-02-2008	6:00 AM - 8:00 AM
	April-05-2008	6:00 AM - 9:00 AM
	April-06-2008	6:00 AM - 7:00 PM
	April-07-2008	6:00 AM - 8:00 AM
	April-14-2008	6:00 AM - 3:00 PM & 5:00 PM - 8:00 PM
	April-15-2008	6:00 AM - 2:00 PM
	April-21-2008	7:00 PM - 8:00 PM
	April-22-2008	6:00 AM - 6:00 PM
	April-28-2008	10:00 AM - 1:00 PM
	April-29-2008	6:00 AM - 8:00 PM
	April-30-2008	6:00 AM - 8:00 PM

3.3.1 Data Collection Setup

Highway 2 and 84th St. was instrumented with three WAD to record individual vehicle information. Two SmartSensor Advance WAD, utilizing digital wave radar technology and installed on the research pole, tracked vehicles upstream and downstream of the pole, recording their distance, speed, lane, and vehicle length up to a distance of 500 ft. A SmartSensor HD acted as the midstream sensor and recorded vehicle information equidistant with the research pole. In addition to recording speed, the SmartSensor HD identified the lane in which a vehicle was traveling, and also recorded vehicle length. The overall data collection schematic is shown below in figure 3.3.

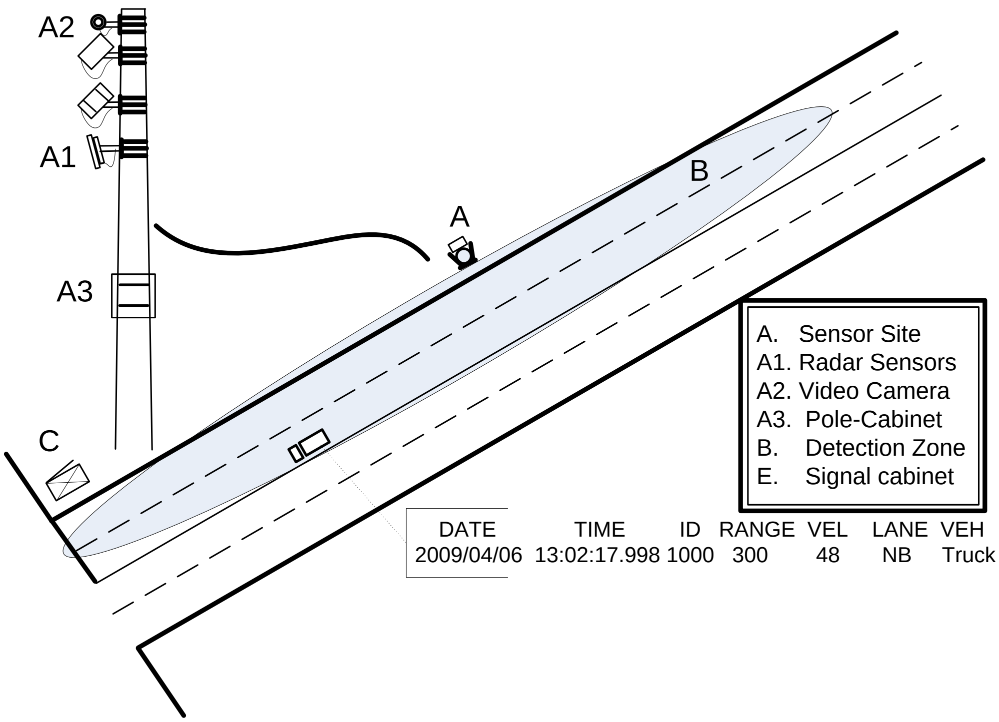


Figure 3.3 Schematic of data collection at Highway 2 and 84th St.

Figures 3.4 and 3.5 display images of the SmartSensor Advance and SmartSensor HD, respectively. Two Click! 500 programmable controllers were used in the field. Signal status was collected by a Click! 500 installed at the traffic cabinet and sent through fiber to a second Click! 500 installed on the research pole. The second Click! 500 extracted the data from three Click! 200 s, one for each WAD, and consolidated the information.

Figure 3.4 Visualization of Wavetronix SmartSensor Advance

Figure 3.5 Visualization of Wavetronix SmartSensor HD

Time synchronization was maintained with reference to the research pole's Click! 500 real time clock. The phase-reading Click! 500 receives updates from the research pole's Click! 500 over fiber optic cable. The time stamping for all three WAD was performed by the research pole's Click! 500. The upstream and downstream latency was 21 ms, while the midstream sensor latency was 6ms.

In addition to the three WAD installed at the data collection site, three cameras were placed to record vehicle movement through the site. Two Axis 232D+ dome cameras, shown in figure 3.6, were mounted on the research pole. These cameras recorded vehicular movement upstream and downstream of the research pole, while the third Axis camera was mounted on the mast arm. Figure 3.7.7 illustrates the three vehicular movement views recorded.

Figure 3.6 Visualization of Axis 232D+ dome camera

Figure 3.7 Display of recorded vehicular movement through data collection site

Data from the WAD was collected through placing a serial cable connecting the RS-232 on the Click! 500 to a CPU in the research pole. Matlab was used to open the serial connection and save the data. The three cameras were displayed on the computer screen using Active Webcam, which captured images at up to 30 fps. Finally, Hypercam 2 was used to record the screen captures from Active Webcam, as shown in figure 3.7.

3.4 Validation

The WADs were validated against the Xsens MTi-G, an integrated GPS and Inertial Measurement Unit (IMU). In addition to capturing the vehicle position from the GPS unit, the MTi-G provided measurement of vehicle acceleration in the X, Y, and Z direction at a rate of 100 data points a second. Setup of the MTi-G is shown below in figure 3.8.

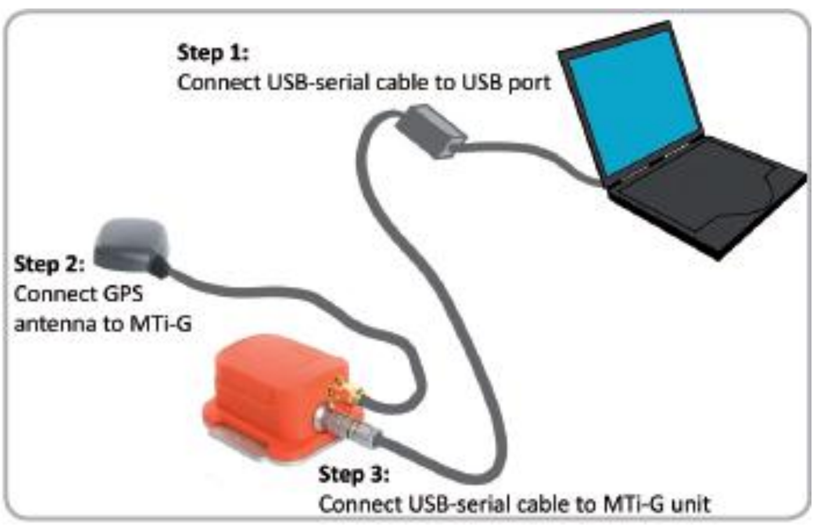


Figure 3.8 MTi-G Setup

A compact car was used as the vehicle for the validation runs. The times were manually synced using a handheld GPS device. An example of the tracking performance of the MTi-G and WAD is shown in figure 3.9. The root mean square error (RMSE) in distance was reported as 9.6 ft.

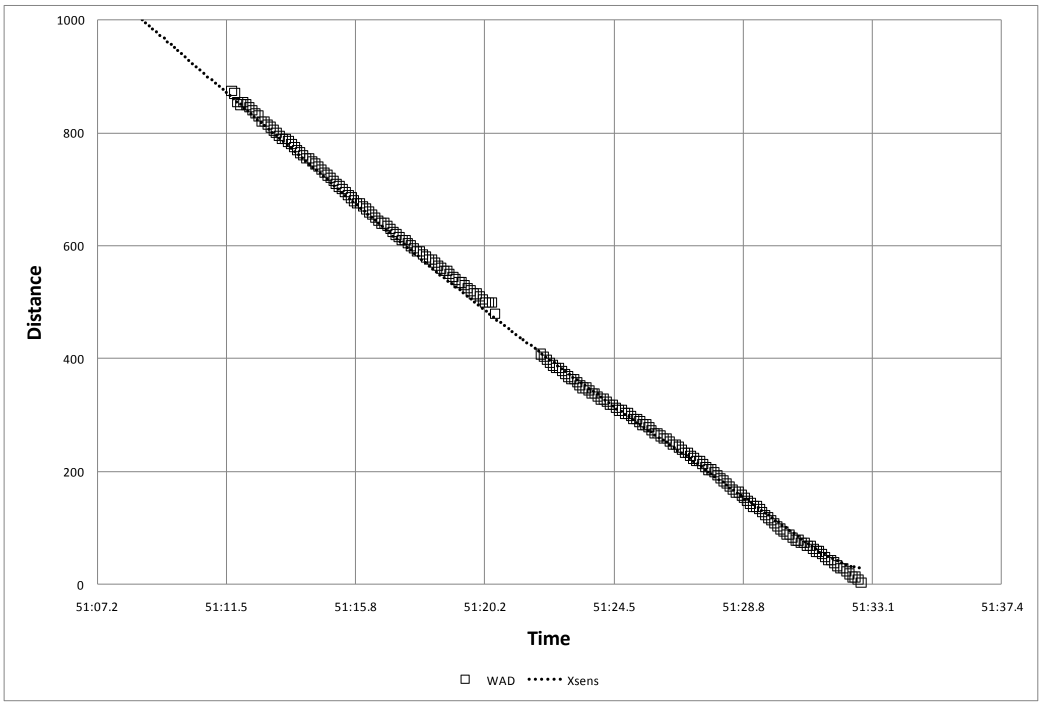


Figure 3.9 Example comparison between WAD and Xsens

3.5 Mobile Trailer Data Collection Setup

Data from the remaining sites located in Nebraska were collected using a portable trailer, as shown in figure 3.10. To use the portable trailer required good weather conditions, as strong continuous or gusty wind would cause the trailer's mast arm to sway. Data was collected on days when there was no precipitation and wind gusts speeds were below 10 mph.

Figure 3.10 Mobile data collection trailer

Similar to the setup described in the previous section, the data collection trailer was equipped with three WAD. Two SmartSensor Advance WAD installed on the pole tracked vehicles upstream and downstream of the pole, with the SmartSensor HD acting as the midstream sensor. Two Click! 500 programmable controllers were also used. Signal status was received from the Click! 500 installed at the traffic cabinet through the portable signal phase reader, shown below in figure 3.11.

Figure 3.11 Safe Track portable signal phase reader

The signal phase reader communicated the signal phase status via radio to the portable sensor pole cabinet. This cabinet featured three Click! 200 s that collected the data from each detector and sent it to the Click! 500; thus, the Click! 500 in the pole cabinet received the data from the signal and all three detectors. Figure 3.12 displays the portable sensor pole cabinet.

Figure 3.12 Portable sensor pole cabinet

Time synchronization with the portable system was maintained with reference to the trailer's Click! 500 real time clock. The phase-reading Click! 500 received updates from the trailer's Click! 500 through the wireless link. When both of these systems were properly synced, drift was less than 70ms. Time stamping for all three WAD was performed by the trailer's Click! 500. The upstream and downstream latency was 21 ms, while the midstream sensors latency was 6ms. The calculated drift in synchronization for the entire system was 97ms, obtained by adding the following component drifts:

- 70ms for the phase information
- 21 ms for the upstream and downstream sensor
- 6ms for the midstream sensor

The entire system had a time resolution accuracy of at least 1/10th of a second. The data was pushed from the Click! 500 using the device's serial port and a serial to USB converter that connected to a laptop. Matlab opened the serial port and saved the data in both .DAT and .txt files. The data was manually trothed through the use of a Mobotix Q24M camera (fig. 3.13). This fisheye camera was able to record high-resolution views, with a frame rate of up to 30 fps. As shown in figure 3.14 (next page), the camera was setup to view upstream, midstream, and downstream of the trailer.

Figure 3.13 Mobotix Q24M camera

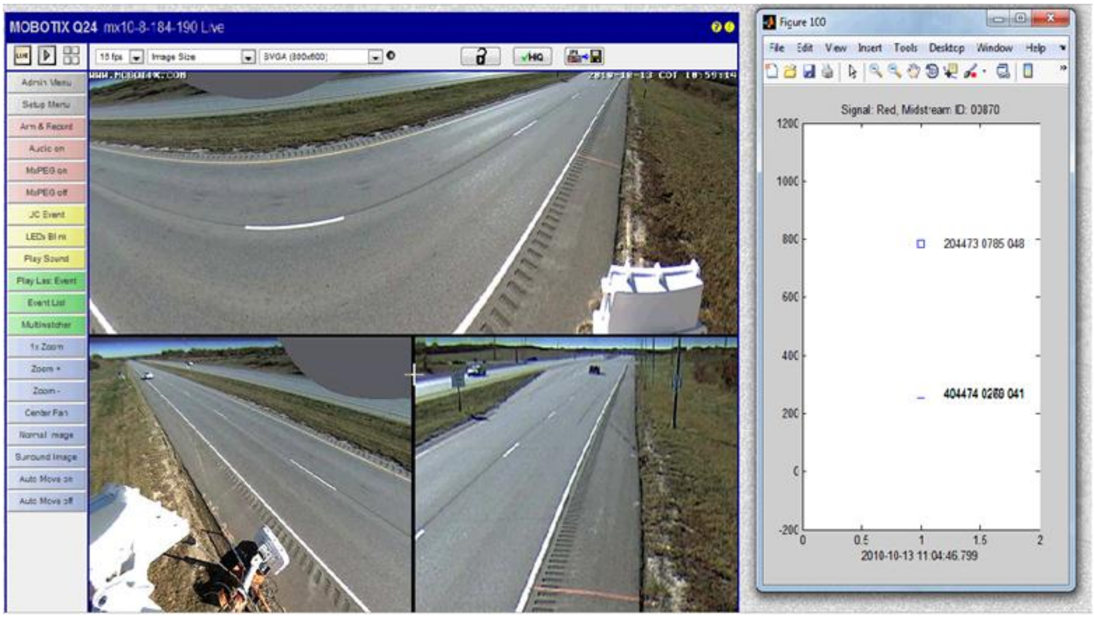


Figure 3.14 Mobile trailer data collection environment

3.5.1 Mobile Trailer Validation

The portable trailer WADs were validated against the MTi-G unit once; however, GPS runs were made using a handheld GPS device each day of data collection in order to ensure accurate vehicle tracking. A pickup truck was used for validation runs. The times were manually synced using a handheld GPS device. An example of the tracking performance of the MTi-G and WAD is shown in figure 3.15. The RMSE in distance was reported to be 12.4 ft.

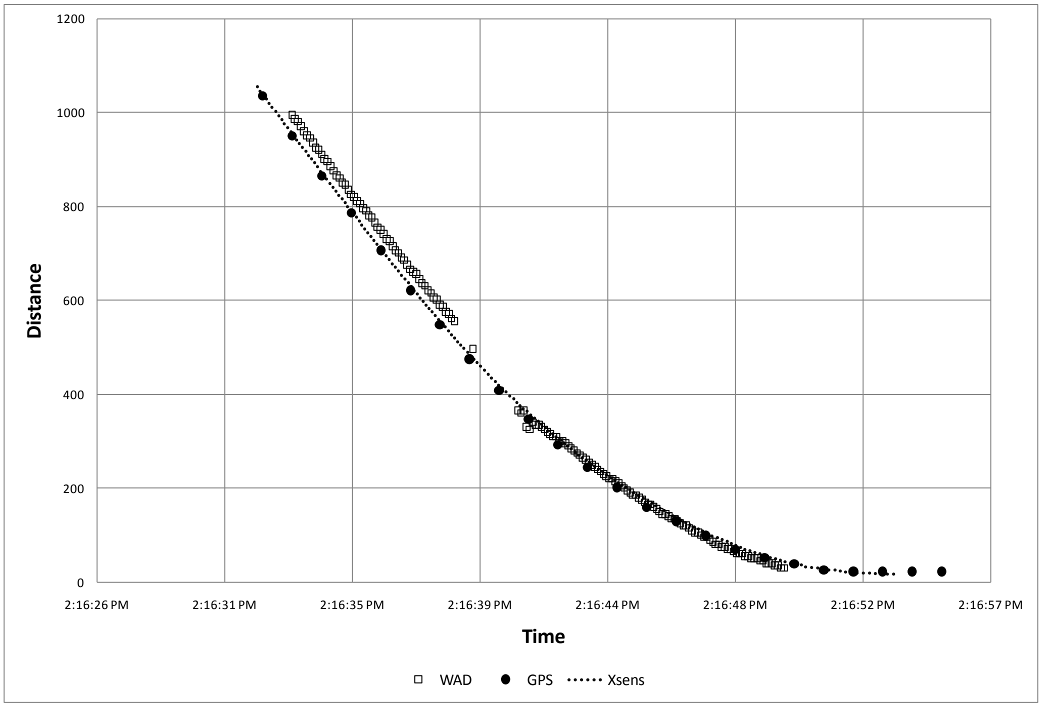


Figure 3.15 Example comparison between WAD, GPS, & Xsens

<u>3.6 Noblesville Site Data Collection Setup</u>

In contrast to the previously studied sites, the Noblesville site had a single WAD, as well as a single camera mounted on the signal mast arm. The WAD and video output were recorded on a computer at a rate of 30 frames per second, as shown in figure 3.16.

Figure 3.16 Data collection environment at Noblesville, IN

3.6.1 Noblesville Site Validation

The WAD was validated against a handheld GPS device after installation. Three vehicle types—a sedan, a pickup truck, and an eight-passenger van—were used as probe vehicles to collect data. Ten runs were conducted for each vehicle type. The time was dynamically synchronized to 0.01 s precision across the data collection computer and GPS device. The RMSE in distance was reported as 7.3 ft. An example of the vehicle tracking by GPS and WAD is shown in figure 3.17. A detailed analysis of the performance of the WAD can be found elsewhere.

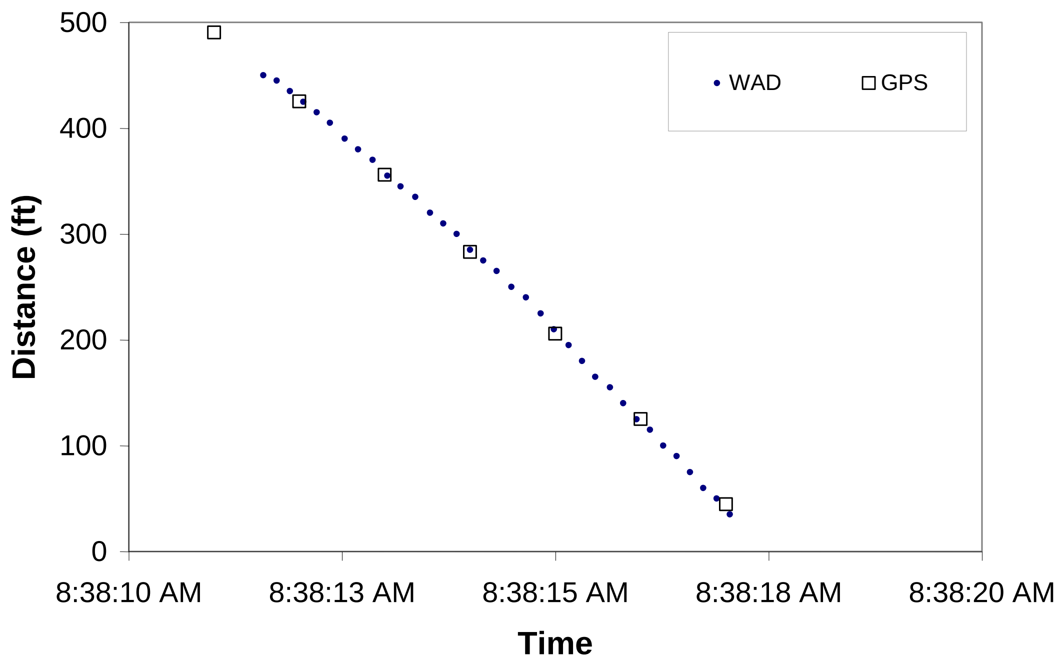


Figure 3.17 Example comparison between WAD and GPS

3.7 Data Reduction

As a result of the video and WAD data simultaneously being captured by Hypercam 2, data reduction was straightforward at most of the sites. However, there were a few dates at Highway 2 and 84th St. when only the video was recorded on the computer screen, with the WAD data being recorded in a text file. Nevertheless, the data was processed in the same manner. The videos were viewed, and if any vehicles were present at the onset of yellow, their downstream Id, range, speed, decision to stop/go, and type of vehicle were recorded. Vehicles were also classified by position: single, leader, or follower. Since the dilemma zone has been defined as the approach area 2.5-5.5 s upstream of the intersection, a time of 3 s was used as the critical headway in determining the interaction between two vehicles. Vehicles with headway values greater than 3 s would not both be in the dilemma zone at the same time; therefore, these vehicles were classified as single vehicles. If the headway was less than 3 s, the interaction was classified as leader (for the first vehicle) and follower (for any vehicle after the leader). In addition, if the driver ran the red light, it was noted. A sample data reduction form is shown in figure 3.18 below:

	Wave	Vehicle present control region					
		Lane SB					
Date	Green end	Downstream ID	Range	Speed	Stop/Go	Conflict	Type
11/15/2010	42:22.4	445	94	63	Go		Truck S
11/15/2010	44:22.4	703	326	36	Stop		Car S
11/15/2010	48:22.5						
11/15/2010	50:22.5						
11/15/2010	52:22.5	555	179	47	Go		Semi S
11/15/2010	54:22.5	685	23	58	Go		Minivan S
11/15/2010	58:22.6	918	102	48	Go		Car L
11/15/2010		920	226	52	Go		Car F
11/15/2010	00:22.6						
11/15/2010	02:22.6	1038	194	47	Go		Car S

Figure 3.18 Sample data reduction form

Other than the Noblesville site, each vehicle was assigned three distinctive vehicle Ids as a result of using three WAD to track the vehicles. The downstream Id was primarily the only Id recorded; however, there were drops in the WAD coverage area between the upstream and midstream, and midstream and downstream detectors, of approximately 50 and 100 ft, respectively. If at the onset of yellow a vehicle was present between the midstream and downstream detectors, the data for all detectors was fit using either a linear or two-degree polynomial, as shown in figures 3.19 and 3.20.

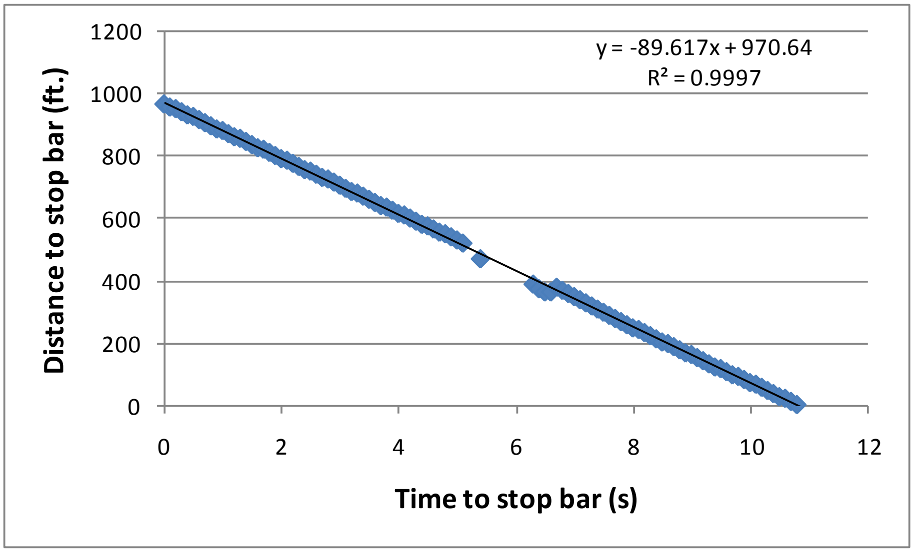


Figure 3.19 Example of linear fit to vehicle

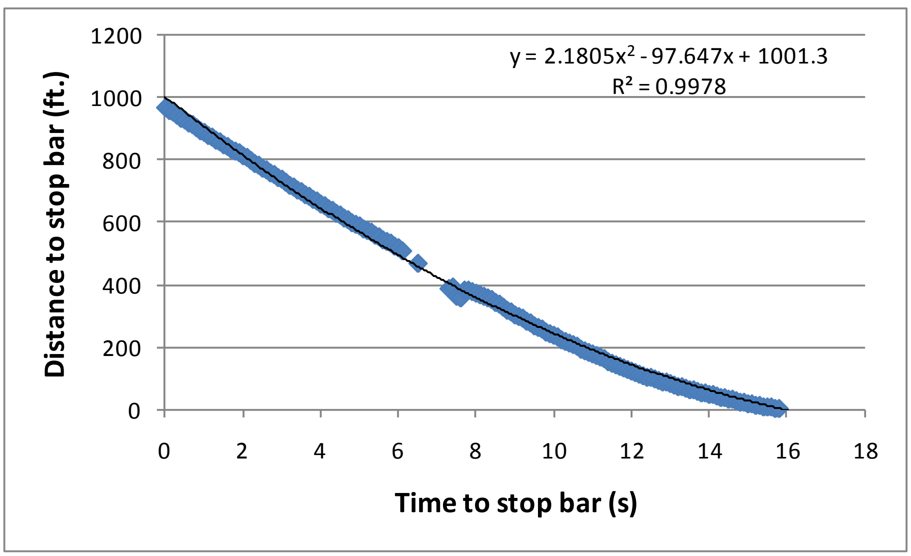


Figure 3.20 Example of two-degree polynomial fit to vehicle

3.8 Summary

This chapter described the data collection and evaluation sites, along with the dates and times of collection. The equipment, software, and setup used in the field to collect the data were explained. In addition, figures presented the calibration of the three systems with GPS units. Finally, the method of data processing was described.

Chapter 4 Role of Information on Dilemma Hazard Function

4.1Theory Underlying Driver Decision Making

Driver behavior at the onset of yellow is essentially a binary choice process in which the driver chooses from two possible courses of action: stop or go (Sheffi and Mahmassani 1981). Let T_p be the time to the stop bar perceived by a driver randomly selected from the population; as a result of the variance in driver behavior based on several independent factors such as perception of the distance from the stop bar, perception reaction time, perception of the yellow interval based on past experience, etc., T_p can be modeled as a normally distributed random variable, as shown below in equation 4.1.

$$T_p = T_{req} + \xi \qquad (4.1)$$

where,

T_{req} is the required time to stop bar;

ξ: is a random variable which is assumed to be normally distributed.

Similar analyses have been performed using the perceived and required time to the stop bar and the perceived and required acceleration (Sheffi and Mahmassani 1981; Sharma et al. 2010). If the perceived time to the stop bar is less than a certain critical time threshold, the driver decides to stop; if the time is greater than this threshold, the driver decides to go. The critical time threshold for a given site can be estimated by the probability of stopping curves. At the point at which the required time to stop bar is equal to the critical time threshold, the probability of stopping is 0.5. Under ideal weather conditions, and assuming the vehicles are passenger vehicles, the critical threshold should be equal to the designed yellow time; this implies that if the perceived time to the stop bar is greater than the provided yellow time, the driver will decide to stop, whereas if the perceived time to the stop bar is less than the provided yellow time, the driver will decide to go. It should be noted that error in driver perception of yellow time can be added to driver perception of travel time error if we assume the yellow duration error to be normally distributed as well.

Two other critical thresholds can be calculated for a driver approaching the intersection at the onset of yellow: the distance requiring severe deceleration and the distance at which a driver would accelerate heavily or run the red light. The following calculations were performed as examples of the acceleration and deceleration threshold, based on 85th percentile acceleration and deceleration values derived from Sharma (2008). The distance at which a vehicle cannot proceed through the intersection without heavily accelerating or RLR is calculated by:

$$Distance_{Accel} = speed \times yellow + \frac{1}{2} \times a \times (yellow - PRT)^2 \qquad (4.2)$$

where,

speed is the speed of the vehicle at the onset of yellow (ft/s);

yellow is the length of yellow (s);

a is the 85th percentile acceleration, 3.19 ft/s^2 (Sharma 2008);

PRT perception reaction time of 1 s.

For a speed of 80.667 ft/s (55 mph) and a yellow length of 4.9 s, the critical acceleration distance equals 420 ft. This distance will be referred to as the maximum passing distance for the remainder of this report, and will represent the critical acceleration threshold. A vehicle at the onset of yellow upstream of this fixed distance, choosing to proceed through the intersection, will require heavy acceleration or will run the red light. Similarly, a fixed distance can be calculated where a vehicle will be require to decelerate heavily, as shown in equation 4.3.

$$Distance_{decel} = \frac{speed^2}{2 \times d} + speed \times PRT \tag{4.3}$$

where,

d is the 85^{th} percentile deceleration, 14.41 ft/s^2 (Sharma 2008).

Again, using 80.667 ft/s (55 mph) and a 4.9 s yellow interval, the severe deceleration distance is computed to be 306 ft. A similar recommended severe deceleration rate of 14.76 ft/s^2 can be found in Malkhamah et al. (2005). A vehicle downstream of this distance choosing to stop will be required to decelerate heavily to stop prior to the stop bar. The two critical threshold distances previously calculated are shown in figure 4.1.

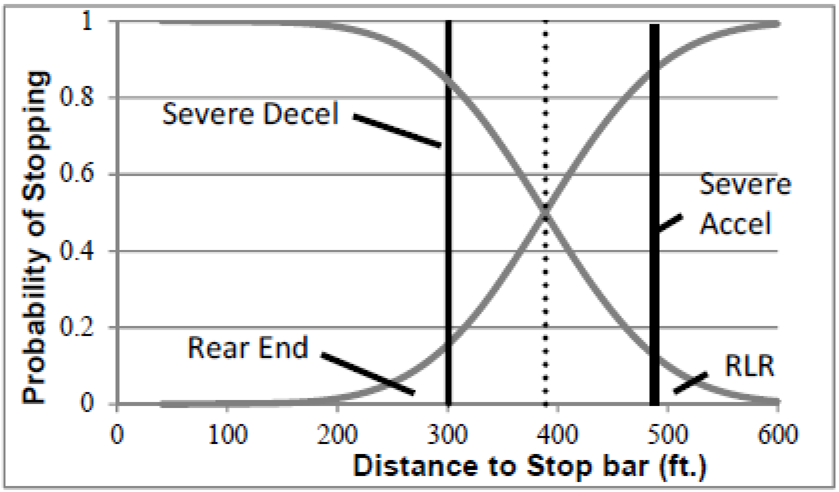


Figure 4.1 Critical distances along probability of stopping curve

4.2Traffic Conflicts

Drivers choosing to stop downstream of the severe deceleration distance or to proceed upstream of the maximum passing distance have made an erroneous decision. The consequences of a driver making an erroneous decision at the onset of yellow can lead to a conflict, and in the previously mentioned cases, a severe conflict. The probability of perceived conflict can be calculated using the critical thresholds and stopping probabilities, as shown below in equation 4.4.

$$P_{CONFLICT} = \begin{cases} P_{STOP} & \forall D_{req} < D_t \\ P_{Go} = 1 - P_{STOP} & \forall D_{req} > D_t \end{cases} \tag{4.4}$$

where,

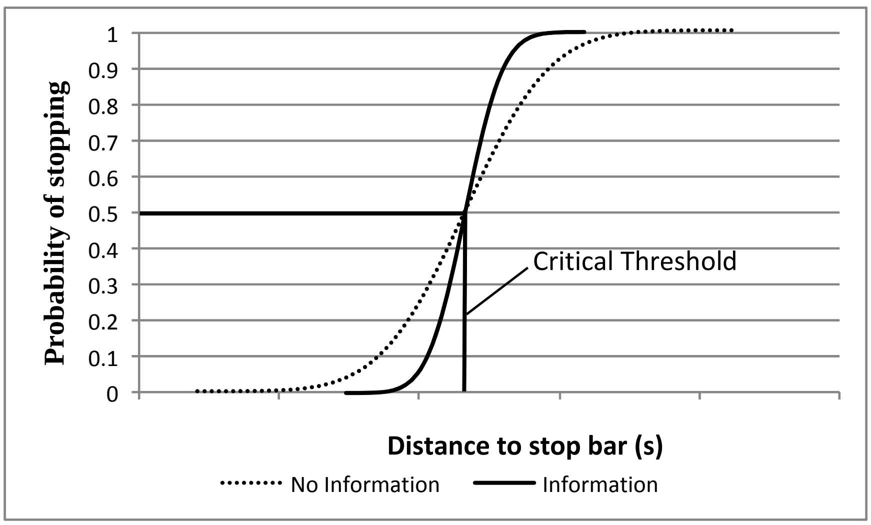
D_{req} is the required distance to perform chosen decision;

D_t is the critical distance threshold dependent on yellow time.

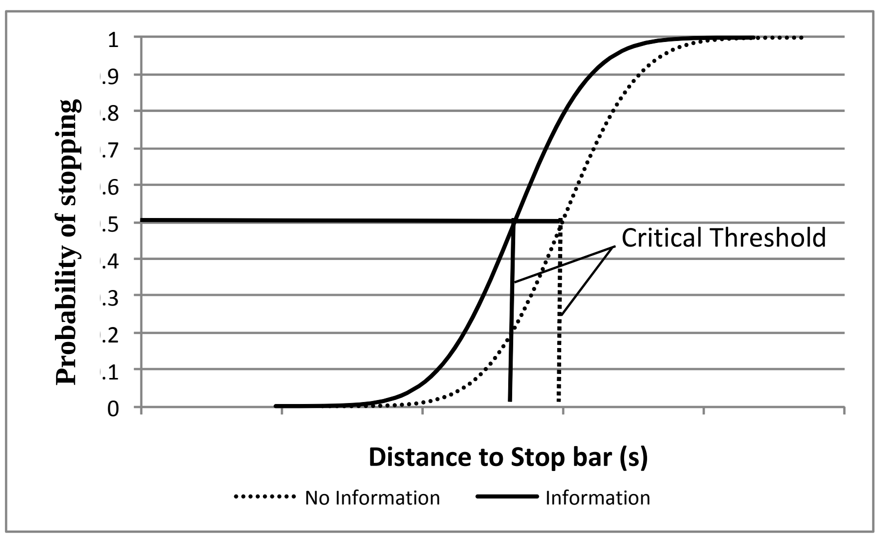
Perceived conflicts can be classified as minor or severe, based on the magnitude of the acceleration or deceleration required to perform the chosen decision, and the typical ranges of acceleration or deceleration used by drivers. The acceleration or deceleration required to complete the chosen action therefore can be used to determine the severity of the evasive action. If the required acceleration or deceleration is within the typical operating ranges, a minor traffic conflict would likely occur; but if the required acceleration or deceleration is greater than the thresholds of the typical ranges, a severe traffic conflict would likely occur. Drivers in the zone of a minor conflict are more likely to experience minor traffic conflicts, such as abrupt stops, applying the brakes before proceeding, or accelerating through yellow. However, drivers in the zone of severe conflict are likely to have severe traffic conflicts such as RLR, swerving to avoid a collision, or vehicle skidding.

4.3 The Effect of Information

Providing drivers with information through AWF has been shown to alter probability of stopping curves (Koll et al. 2004). There are two potential impacts of providing information to drivers: (a) the probability of stopping curves become steeper due to reduced perception error, as shown in figure 4.2a; note that threshold value is not affected, and both curves have the same midpoint. Ideally, the slope of the probability of stopping curve is infinity, implying that every driver makes the correct decision at the onset of yellow; (b) the threshold value (perceived duration of yellow) changes, thus, shifting the probability of stopping curve, as shown in figure 4.2b; the probability of stopping curve could be shifted closer or farther from the intersection. Recalling that the probability of a conflict is dependent upon the probability of stopping, and that the two critical thresholds are fixed results in a shift in the probability of conflict curve, it follows that, if the probability of stopping curve were shifted closer to the intersection, the probability of severe deceleration would increase. Conversely, a shift in the probability of stopping curve farther from the intersection would result in an increase in RLR. This research will examine the effects of information on the potential shift in the midpoint, as well as on the change in slope of the probability of stopping curves.



a) Change in variance



b) Change in threshold

Figure 4.2 Effect of information provided to drivers

4.4 Data Analysis and Results

4.4.1 Best Fit Model Parameters

At the onset of yellow, a driver can choose from two mutually exclusive courses of action: stop or go. This decision process can therefore be modeled using binary discrete choice models. Based on the approach followed by Sheffi and Mahmassani (1981), a probit model was used to investigate the influential independent variables for driver decisions at each intersection.

The independent variables tested are listed below:

- time to stop bar;
- distance to stop bar;
- speed at onset of yellow;
- deceleration required to stop the vehicle within the stop bar;
- acceleration required by the vehicle to cross the stop bar prior to onset of red.

An extensive analysis was performed on these variables in order to determine the set of instrumental variables affecting driver decisions. The maximum likelihood estimation technique was used to obtain estimates of the parameters using NLOGIT (2007). Models were compared using Akaike's Information Criterion (AIC) (AIC 2009). AIC takes into account both the statistical goodness of fit and the number of parameters required to obtain the goodness of fit. As the number of model parameters increases, a penalty is imposed upon the model. The best or preferred model is the model that has the lowest AIC value. Results of the analysis showed that the best-performing model was time to stop bar and a constant, as shown in table 4.1.

Table 4.1 Probit model results

	AIC Value	Log likelihood function
Site 1	0.43284	-32.62681
Site 2	0.51298	-110.0872
Site 3	0.44859	-35.23322
Site 4	0.42807	-28.82094
Site 5	0.52098	-62.34153
Site 6	0.28287	-386.5199

4.4.2 Dilemma Zone Boundaries and Effect on Stopping

The final estimated parameters were used to develop probability of stopping curves for a speed of 55 mph at each site, as shown below in figure 4.3. The probability of stopping curves revealed the effect of information provided to drivers by the AWF. The three Nebraska Department of Roads (NDOR) sites (Site 1, Site 3, and Site 4) and Site 6 were relatively similar, with Site 1 and Site 4 having essentially identical curves. As shown previously in table 3.1, Site 1 and Site 4 operated identically, with the flashers starting 7 s before yellow and with a yellow time of 4.4 s. Site 6, the only site without AWF, had the longest probability of stopping and the largest dilemma zone. Information provided to the drivers at the Site 2 caused a dramatic shift in the probability of stopping. Under the authority of the City of Lincoln, Site 2 site is operated differently than the NDOR sites.

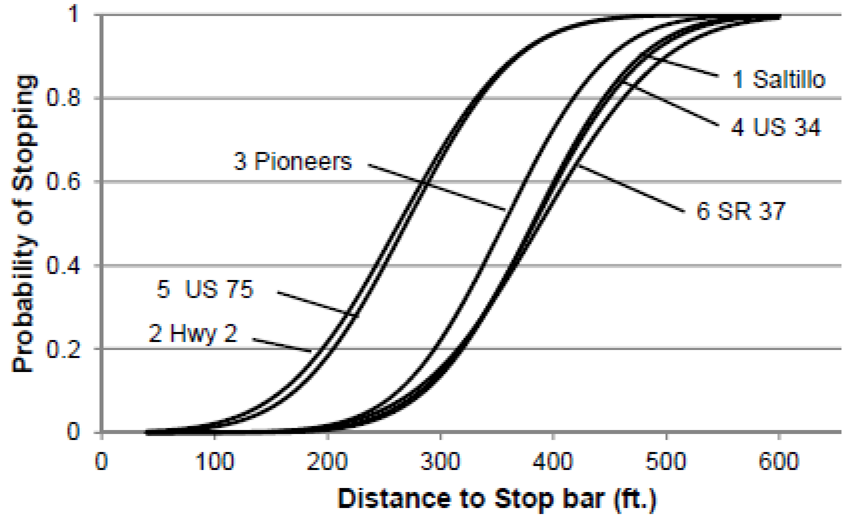


Figure 4.3 Probability of stopping curves

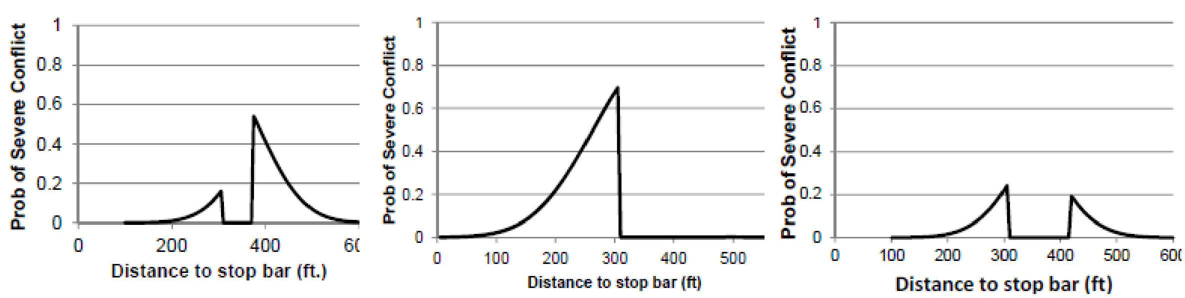
The main distinctions between Site 2 and the NDOR sites were, first, that the AWF at Site 2 were 87 ft closer to the stop bar than at the three NDOR sites; moreover, the sum of the yellow time and the amount of time before yellow when the advance warning flashers activate was 0.7 s longer at Site 2 than at Site 3, and 2.2 s longer than at Sites 1 and Site 4.

It appears, as is illustrated in figure 4.4, that when drivers were presented with information (yellow time and time before yellow AWF activate) for a longer time period, their probability of stopping earlier increased. Site 2 and Site 3 presented information to drivers for the longest amount of time, while Site 6 did not present drivers with any information prior to the onset of yellow.

Figure 4.4a illustrates the dilemma zone hazard curve at Site 4. The severe deceleration and maximum passing distance were the critical thresholds for severe conflicts. The risk of conflict increased until reaching the maximum passing distance. Figure 4.4a also illustrates that a large percentage of drivers were predicted to make erroneous decisions at the onset of yellow, based on the severe deceleration and maximum passing thresholds. In particular, a sizeable percentage of drivers were predicted to either accelerate heavily or run the red light; thus, potentially causing a right angle collision.

As shown below in figure 4.4b, the drastic shift in the probability of stopping at Site 2 caused virtually every driver approaching the intersection to potentially have a severe conflict. Based on the yellow time of 5.6 s and the posted speed limit of 55 mph, a driver traveling at the speed limit could pass through the intersection from a distance of 485 ft at the onset of yellow. While the length of yellow significantly decreased the possibility of an RLR, the information provided to the driver from the AWF was telling them otherwise, resulting in a significantly large number of predicted severe conflicts, such as abrupt stop, heavy deceleration, or vehicle skidding. Evidence that longer yellows decrease the percentage of RLR is also found in (Bonneson et al. 2002), while, similar to Koll et al. (2004), providing drivers with information leading to early stops can increase the possibility of severe rear-end collisions.

As shown in figure 4.4c, when information was provided correctly, it decreased the risk for drivers approaching the intersection. The predicted severity risk of crashes at Site 3 site was significantly lower than at the other studied sites.



a. Site 4 US 34   b. Site 2 Hwy 2   c. Site 3 Pioneers

Figure 4.4 Probability of severe conflicts at different sites

Weighted risk was calculated by first integrating the area under both severe conflict thresholds. An average of the integration was computed. Lastly, the proportion of vehicles within each speed category was multiplied by the averaged integration, resulting in a weighted average of risk for a driver approaching an intersection. The weighted average risk was found for both critical thresholds. Results of the risk analysis are shown in figure 4.5. As expected, Site 2 and Site 5 had displayed the largest rear-end crash risk, while Site 1 and Site 4 demonstrated the largest risk of red light running.

Actual severe conflicts were totaled and proportioned for all site vehicles requiring a deceleration rate of 14.41 ft/^{s} or higher as well as the observed RLR. Similar to the weighted risks, a trade-off was found between the proportion of vehicles requiring severe deceleration and red light running, as shown in figure 4.6. The proportions of risks and conflicts at Sites 1, 2, 4, and 5 were almost in complete agreement with the calculated risks and accident histories. The calculated risks and proportions of severe conflicts displayed a good correlation; however, at Site 3, the proportions switched.

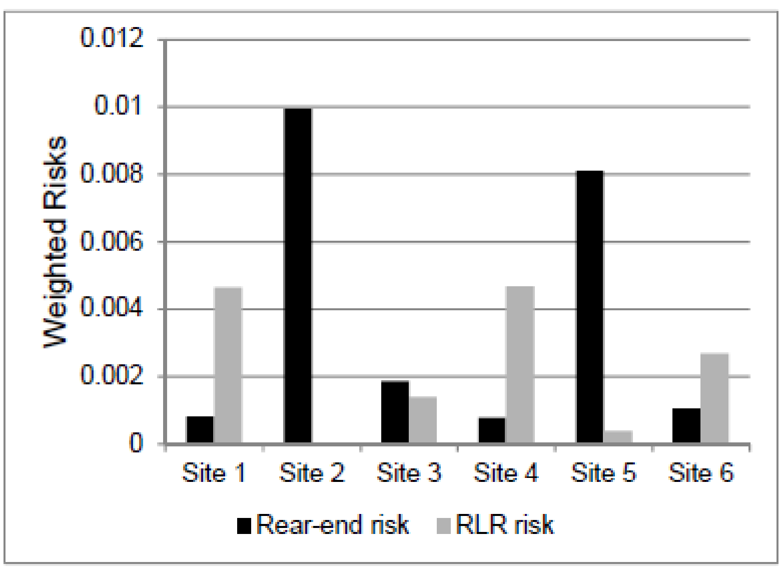


Figure 4.5 Calculated weighted risks

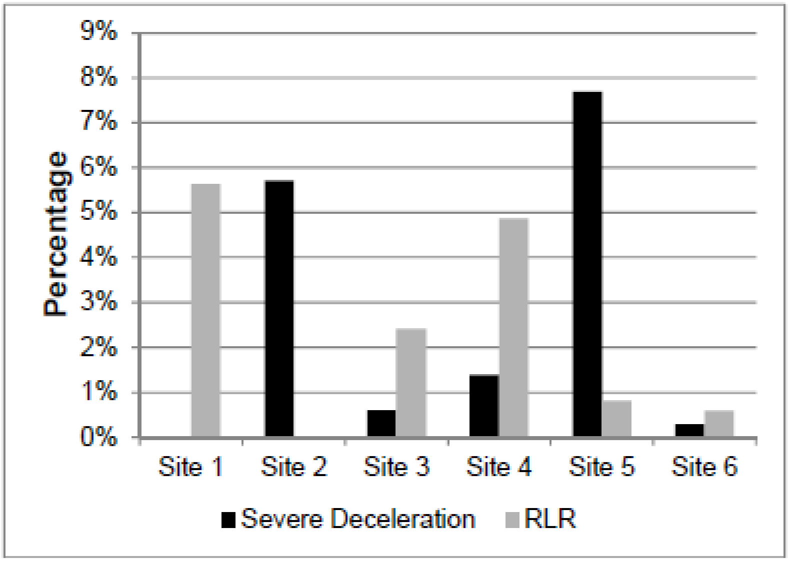


Figure 4.6 Proportion of vehicles performing sever deceleration or RLR

4.5 Discussion

Figures 4.4 a and b display a large percentage of drivers at risk of a severe conflict. Having such large percentages of drivers at risk of severe conflicts is problematic. Figure 4.7 illustrates the probability of stopping under four different conditions. Curves A and D represent intersections where the majority of drivers performed erroneous decisions. Similar to the results from Site 2, drivers approaching the intersection represented by Curve A will put all the drivers at risk of severe stopping. Curve D shows that a significantly larger percentage of drivers were predicted to accelerate heavily or to run the red light. The stopping curve represented by Curve C was noticeably improved in terms of providing drivers with protection from severe conflicts, as the majority of drivers stop between the severe deceleration and maximum passing distances. Ideally, the probability of stopping curve would appear as shown in Curve B, where the decision dilemma zone boundaries are within the thresholds of severe deceleration and maximum passing distance, thus minimizing the risk of severe conflicts at the onset of yellow.

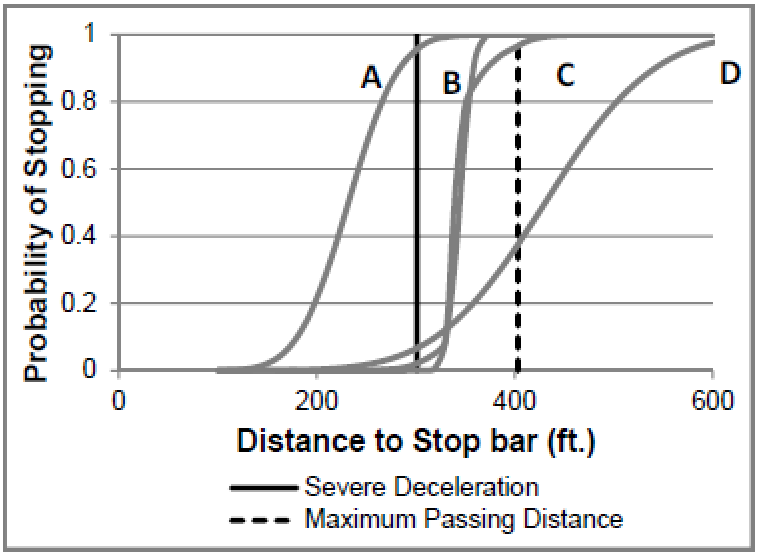


Figure 4.7 Hypothetical probability of stopping curves

Finally, in comparison with previous literature (Koll et al. 2004; Elmitiny et al. 2009; Hurwitz 2009; Wei et al., 2009) the calculated perceived yellow time length versus actual length was plotted as shown in figure 4.8. Intersections with AWF, or, in the case of Koll et al. (2004), flashing green, were plotted separately from intersections that did not provide drivers with information. Four intersections from Hurwitz (2009) were graphed; however, the perceived time and actual yellow lengths for all four intersections was 4 s. Based on this sample of intersections, drivers approaching intersections without being provided information correctly perceived the time threshold, while drivers inaccurately predicted the time threshold at intersections providing them information. One of the reasons for this effect could be the fact that the information provided is not personalized, thus, it leads to more variability. The YODA system can help to alleviate this problem. The largest outliers from figure 4.8 were points A, B, and C, which represent Site 2, Site 5, and Koll's studied sites in Austria. In addition, figure 4.8 displays the type of risk that associated with being above or below the line. The three previously mentioned sites have the potential for increased rear-end crash risk, as these intersections all fall below the line. Conversely, any intersection above the line would have the potential for increased RLR risk. Therefore, while providing drivers with information has been shown to reduce accidents—and in particular RLR (Gibby et al. 1992; Farraher et al. 1999; Messer et al. 2003), the current study suggests that providing information to drivers can increase the risk of accidents. In particular, the risk of stopping conflicts increased with information that was not personalize

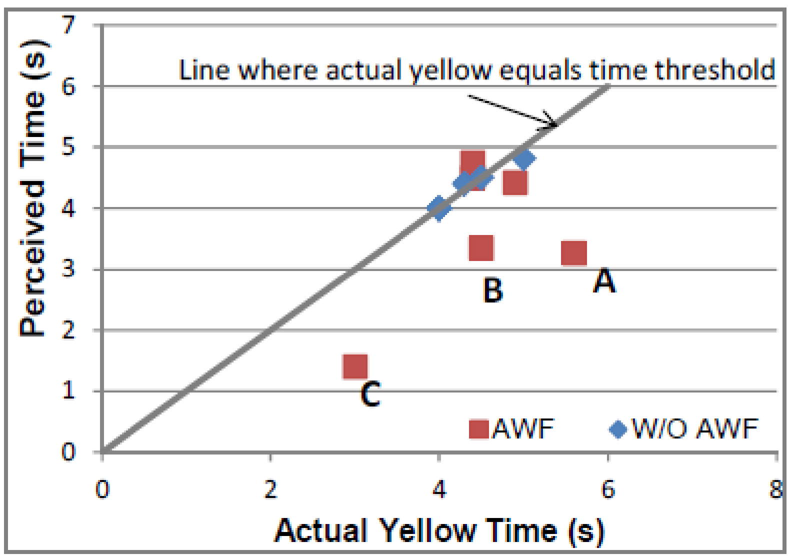


Figure 4.8 Comparison between actual and perceived yellow lengths

<u>4.6 Conclusions</u>

The results demonstrated that AWF systems potentially contributed to increases in both rear-end and RLR crash risks by providing non-personalized or incorrect information to drivers. The major insight garnered from the current study was that any information provided to a driver regarding stop and go decisions should be consistent with the actual duration of yellow time. If the yellow time is longer that as implied by the AWF and the driver is incorrectly signaled to stop, the outcome is more confusion, resulting in higher-risk intersections. It should also be noted that when no information was provided, the critical time threshold for stopping was very close to the actual yellow duration. This shows that drivers usually were likely to stop when the time to the stop bar was greater than the yellow time, and were likely to go when the time to stop bar was less than the yellow duration. The next chapter presents the details of a prototype YODA system, developed for this study, which utilizes this concept to inform stop and go decisions; the YODA system provides personalized information to the driver based on the time to the stop bar and the remaining yellow time.

Chapter 5 Development of the YODA System Prototype

5.1 Introduction

The previous chapter provided a detailed discussion on the role of information in aiding driver decisions at the onset of yellow. The YODA system was designed to aid drivers by providing personalized information at the onset of yellow. The system collects phase status information from the traffic signal cabinet and obtains speed information from the requesting vehicle. If the requesting vehicle’s time to the stop bar is less than the time remaining to the end of the yellow phase, the vehicle is said to be at a low risk; in the opposite case, the vehicle is notified to reduce speed and prepare to stop. The architecture used by the YODA system is “V2I” (Vehicle to Infrastructure) (RITA 2012). With V2I, a Dedicated Short Range Communication (DSRC) (Armstrong Consulting, Inc., 2012) equipped vehicle communicates with the roadside infrastructure. Figure 5.1 shows the equipment used to implement the YODA system.

Figure 5.1 Savari network (Savarinetworks 2012) devices, StreetWave on left and MobiWave on right

The setup consists of two devices, MobiWave and StreetWave. MobiWave is the in-vehicle device; it is connected with a driver interface, and is equipped with a GPS device. StreetWave is installed at the intersection and is connected to the traffic light in order to obtain signal information from the light.

Using MobiWave, vehicle speed and location of the vehicle are sent to the StreetWave. Then StreetWave compares this information to the phase status obtained from the traffic light. For green and red signals, driver decisions are straightforward; for yellow signals, however, drivers can choose to either stop or go. StreetWave assists the driver of the vehicle by computing whether or not the vehicle can safely clear the intersection safely before the onset of the red signal. If it is safe for the driver to proceed, StreetWave sends the appropriate signal to MobiWave; StreetWave also sends a signal to MobiWave if continuing through the intersection is risky. The driver can see on his user interface screen whether it is safe to continue or if it is necessary to decelerate and stop.

The DSRC (Armstrong Consulting, Inc. 2012) technology utilized by YODA consists of one-way or two-way short- to medium-range wireless communication channels specifically designed for automotive use, as well as a corresponding set of protocols and standard two-way medium range communication channels. The DSRC transmitter and receiver pair are present in both MobiWave and StreetWave so that the systems can communicate with each other.

5.2 Prototype Assembly

MobiWave and StreetWave were connected to a switch using Ethernet ports; then, the switch was connected to a computer equipped with the Ubuntu 12.04 Operating System. The set-up is displayed in figure 5.2.

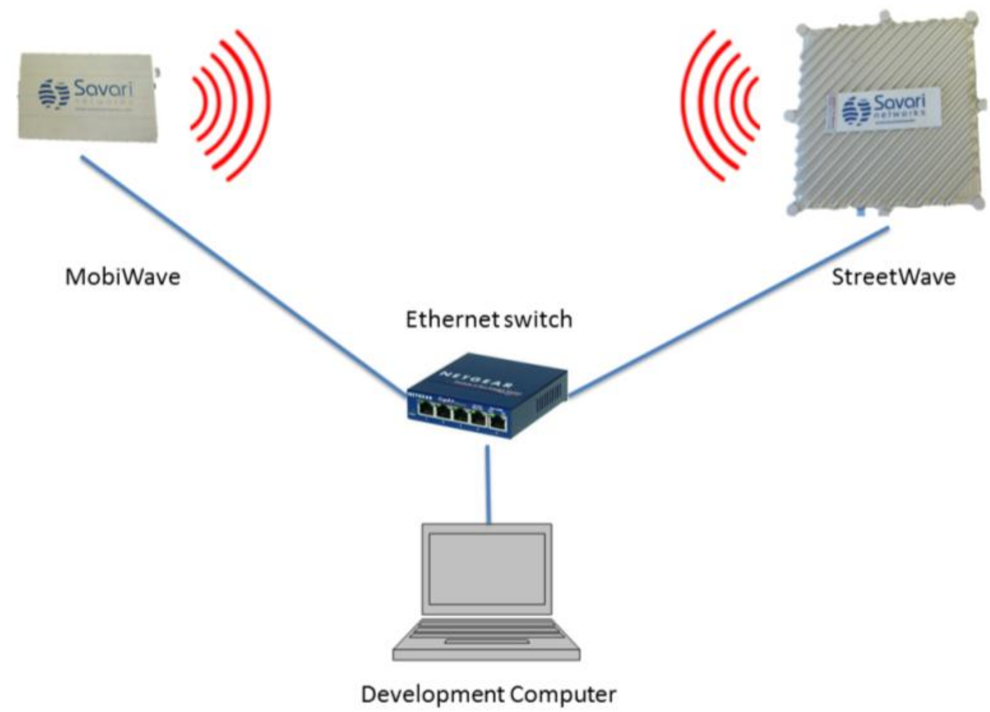


Figure 5.2 Connection set-up for development purposes

The following steps were taken to successfully install our software packages to MobiWave and StreetWave. Please note that throughout this part of the documents all codes are presented in italics.

Step 1 consisted of connecting the development machine to MobiWave/Street Wave. The terminal screen on Ubuntu was displayed by holding Ctrl + Tab and pressing T. Repeating his sequence three consecutive times resulted in opening three different terminals, one for the developing computer, one for MobiWave, and one for StreetWave.

In the terminal opened for MobiWave, entering the command: *ssh root@192.168.0.253* resulted in connecting to the device operating system. First, the password *gems* was entered; following password entry, the operating system was displayed on the terminal assigned to MobiWave, as shown in figure 5.3:

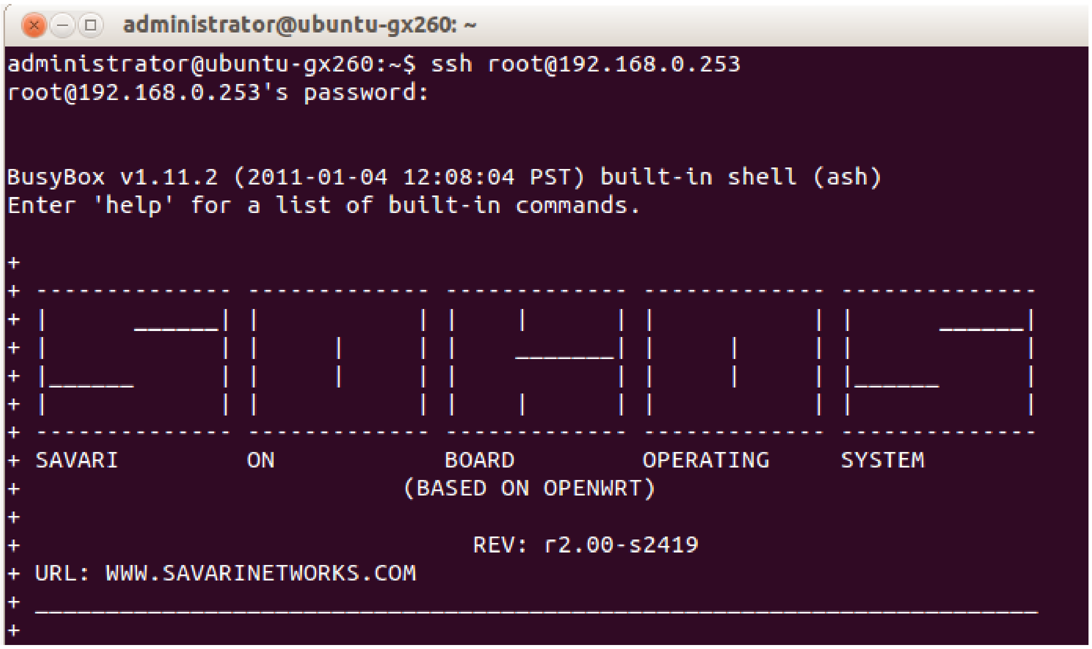


Figure 5.3 Openwrt operating system on MobiWave

The same course of action was taken for StreetWave: the command *ssh* *root@192.168.0.252* was entered, followed by the password was *gems*. An identical screen as that of the MobiWave screen was displayed.

MobiWave and StreetWave operate on an openwrt operating system. A limitation of this operating system is that no code can be directly compiled; instead code is cross compiled. Cross compiling entails that software code is written and compiled on another computer connected to the openwrt systems, then linked to the openwrt operating system. The openwrt receives only executable binary codes. This shields the MobiWave or the StreetWave unit from the compilation load.

Step 2 consisted of loading the vendor-provided package onto MobiWave/StreetWave. Savari Networks provided all of the packages required for enabling cross compiling for the YODA algorithms, and any other desired package. Savari also provided critical device specifications for hardware usage. Since the packages were in compressed format, after the packages were copied onto the development computer they needed to be extracted using the code listed below. The first step, using the terminal specified for the developing computer, was to use *cd* command to arrive at the directory upon which the packages were copied, and enter:

%tar -jxvf SOBOS-X-SDK-x86-for-Linux-i686(correct file name).tar.bz2 (5.1)

Some sample codes were provided by the vendor. In order to enable cross compiling, it was necessary to link the file path where the package intended to be placed on MobiWave/StreetWave, then convert them to binary. First it was necessary to link the simple, vendor- provided *helloworld* package because it generated the correct folder structure, which would be of use in any other desired package. Again using *cd* command prompted the *SOBOS-X-SDK-x86-for-Linux-i686* folder, which is referred as SOBOS in the remainder of this report. The code required for linking a package was as follows:

% ln -s ../../sdk-sample-apps/helloworld (5.2)

where,

ln is a Unix command for linking files or directories to each other.

In the SOBOS folder, the command *make V=99*. *Make V=99* was entered when compiling system output was desired in verbose mode. Verbose mode, by definition, is a mode in which varying levels of status messages are displayed during processing. This command resulted in the creation of a new file in the folder *packages*—*helloworld.ipk*—which was ready to be transferred to the openwrt operating system.

Step 3 involved copying the package on MobiWAVE. On the development computer terminal, using the command below or any other command that used *CD* , the folder packages located in the folder bin were accessed:

cd SOBOS-SDK-x86-for-Linux-i686(correct file name)/bin/packages/i386 (5.3)

There, the package was copied on MobiWave using the instruction below:

scp helloworld.ipk root@192.168.0.253:/tmp (5.4)

scp or, secure copy, copies files between hosts on a network. It uses *ssh* protocol, implying that the data transferred is encrypted and authentication is needed to copy the data. On the terminal that was connected to MobiWave, researchers typed in: *cd /tmp* , which opened the *tmp* folder. Typing the instruction below installed the code on the MobiWave.

opkg1 install ./helloworld.ipk* (5.5)

Opkg is a lightweight package management system based on Ipkg, used in older versions of openwrt. It can install, update, and remove individual software packages, resolve dependencies between packages, and so on. After this command, typing

[1] In the guide it was written 'ipkg,' which will result in an error. In the newer versions of openwrt (such as used here), the correct command is 'opkg.'

/usr/local/bin/helloworld loaded the application, and resulted simply in MobiWave saying: *Hello World!*

The *helloworld.ipk* file on StreetWave can also be copied using the terminal specified to it to obtain similar results.

Step 4 entailed installing specific packages on the MobiWave/StreetWave. The file structure is described in next section in detail. It should be noted that our package contained a file named *its_trafficlight.c*. Once opened, the screen read:

#define CARz. Notably, this differs from "*CAR.*" Anything other than *CAR* was compiled for StreetWave. If *CARz* was changed to *CAR*, it was compiled for MobiWave.

Steps taken here were almost completely identical to the vendor-provided package *helloworld*. The name of the package designed by the researchers was *its_trafficlight*. All the steps were taken exactly as mentioned above, but, instead of *helloworld*, the term *its_trafficlight* was used. However once the package *its_trafficlight.ipk* was generated for StreetWave and copied, the file *its_trafficlight.c* was opened and *CARz* was changed to *CAR*, at which point another *its_trafficlight.ipk* was generated and copied on MobiWave.

Step 5 involved understand the displays on the terminals. As a result of connecting to the terminals of MobiWave and StreetWave, the results obtained while running the code can be seen below. Here 3 scenarios may occur:

A) The MobiWave is not getting any data from StreetWave, and vice versa:

In this case the devices do not communicate with each other. Figure 5.4 briefly describes how each operates in this case:

Figure 5.4a MobiWave not in the range of any StreetWave

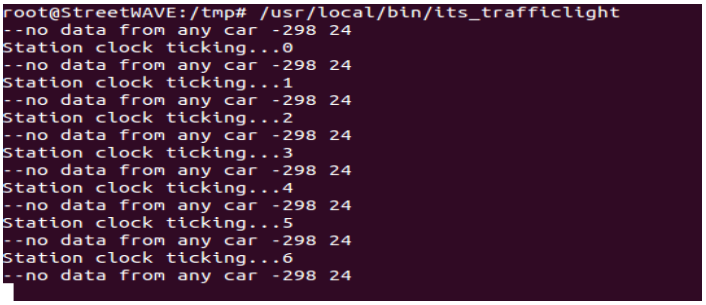


Figure 5.4b StreetWave with no MobiWave detectable

B) Vehicle approaching yellow signal safely:

In this case, the StreetWave has computed the risk depending on speed and distance from the traffic light as well as the remaining yellow signal duration, and has decided that it is safe for the driver to proceed. It communicates a signal to the MobiWave. Figure 5.5 shows how MobiWave translates the signal at the corresponding GPS location on the terminal, and the reaction of StreetWave to inputs from MobiWave and the traffic light.

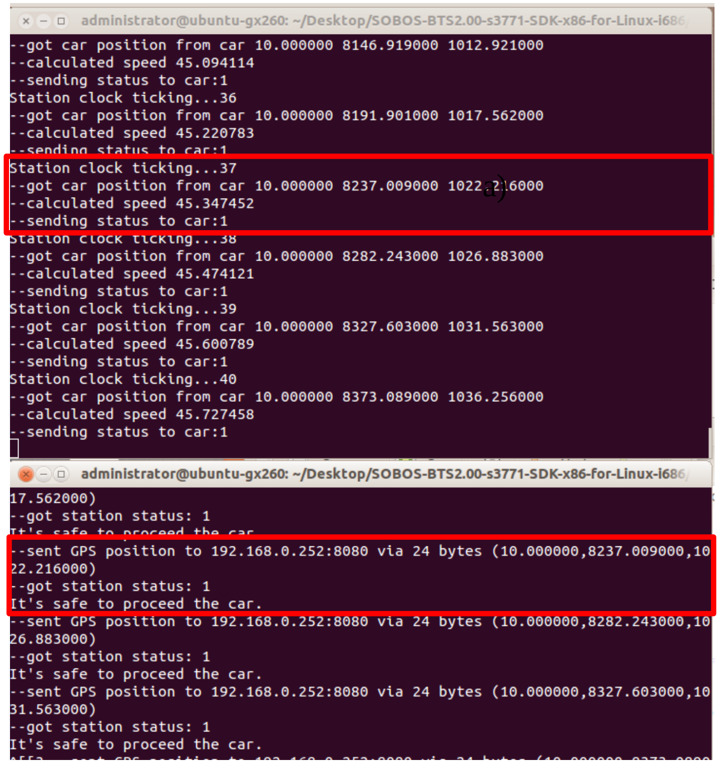


Figure 5.5 A vehicle in the safe mode, on StreetWave terminal, and on MobiWave terminal

C) Vehicle approaching yellow signal unsafely:

In this scenario, the StreetWave decides again that it is not safe for the driver to proceed based on the speed, distance from the traffic light, and seconds remaining from the yellow signal; the system therefore sends a stop signal to the MobiWave. MobiWave shows this result on the terminal, as can be seen in figure 5.6.

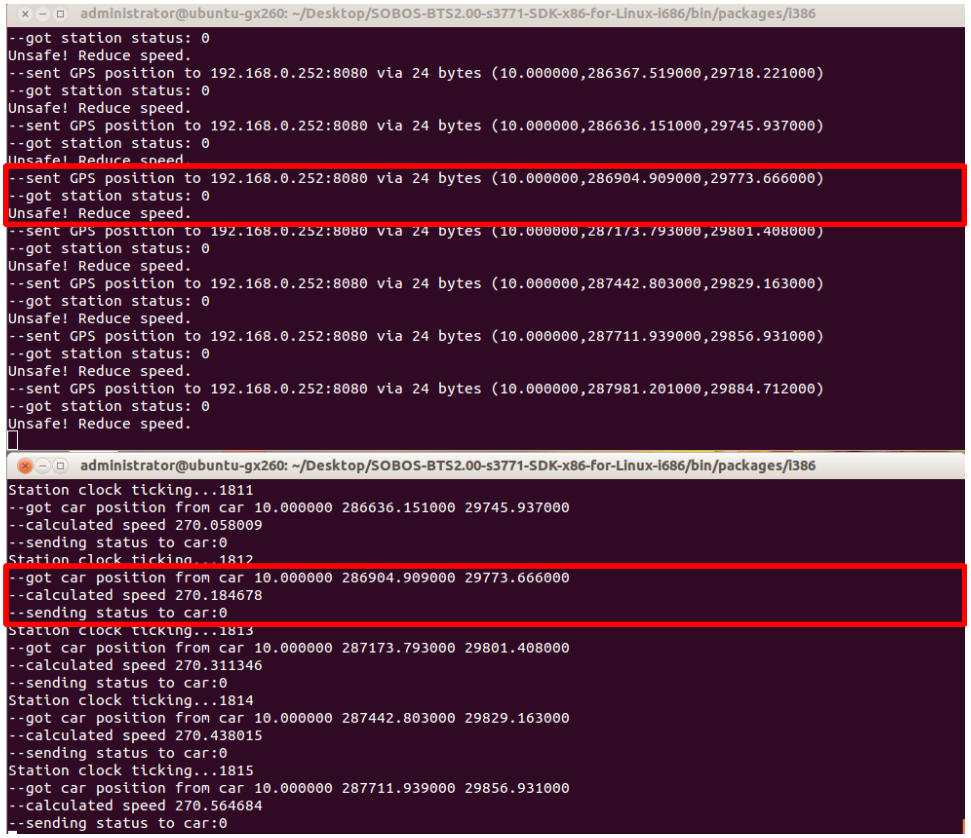


Figure 5.6 Unsafe approach of a vehicle to yellow signal, shown for both MobiWave and StreetWave

5.3 File System

This current section provides an overview of each file. The position of traffic signal station was given manually in a file named "position.txt," and the duration of red, green, and yellow lights were entered in the file "duration.txt." For testing purposes, the ip.txt contained IPs that were not generated for MobiWave and StreetWave; after initial testing, these IPs need to be changed to static IPs provided by the Savari Networks, as described earlier in this report.

5.3.1General.c and General.h.

These header files include the information about the format that is being used by the GPS device in the MobiWave. They also define type of IPs and GPS structure.

5.3.2 UDP.c and UDP.h

UDP stands for user data protocol. For any communication between two or more devices, there should be a protocol to enable the safe and secure transmission of data, and also ensure that the data is transferred in the same manner. All of these details fall under the category of user data protocol, whether the connection between two devices is wired (such as development computer to either MobiWave or StreetWave) or wireless (connection between MobiWave and StreetWave). According to the specifications provided along with MobiWave and StreetWave, these programs use static IPs, which enable developers to use proper socket programming. In any package intended to work with these devices, the MobiWave IP is: *192.168.0.253*, and the StreetWave IP is: *192.168.0.252*. In both cases, TCP port used was *8080* The username was *root*, and the password was *gems.*

5.3.3 Car.c

The code to be housed in MobiWave is written in the file *car.c*. It translates the signal received from StreetWave. This program is also responsible for obtaining GPS position from the GPS device and putting it in the correct format to send over a wireless connection to StreetWave. It should also be noted that whenever Mobiwave is communicating within itself, it should use IP: *127.0.0.1* and port *2947*. This goes for any internal communication between MobiWave and the inbuilt GPS.

5.3.4 Station.c

The program *station.c* was designed for StreetWave. This program is responsible for obtaining the location from the MobiWave and finding the speed. It also receives the information regarding traffic signal status. Finally, it compares the speed and distance with the location of the station (traffic light), and processes whether a yellow signal is being shown and for how long. StreetWave decides if it is risky for the driver to proceed or not, and sends the appropriate signal back to the MobiWave. Figure 5.7 shows the inputs for StreetWave.

Figure 5.7 StreetWave inputs

5.3.5 Its_Trafficlight.c

This file contain logic for both MobiWave and StreetWave with different functions being executed depending on mode choice made by the user. If mode is chosen as *CAR* the functionalities relevant to MobiWave are executed and if mode is defined as anything else the functionalities relevant to StreetWave are executed. This aids in the readability and simplicity of our code.

5.4 Wireless Communication

MobiWave is an on-board-unit capable of providing wireless and wired communication systems. As shown below, GPS is connected to MobiWave, and it sends the data to the StreetWave as soon as it is in the detectable range. StreetWave is installed on a pole at the intersection, where it receives traffic light information. As soon as a vehicle sends its GPS information, StreetWave computes risk and transmits the correct decision in order to assist the driver in the dilemma zone. This communication between the vehicle and StreetWave is classified as DSRC. The DSRC utilized by the GPS and StreetWave is programmed by socket programming, as both devices have static IPs. MobiWave is then connected to a screen using an Ethernet cable to show the driver the preferred decision on whether to accelerate or decelerate. The UML in figure 5.8 describes the order of events in the YODA system.

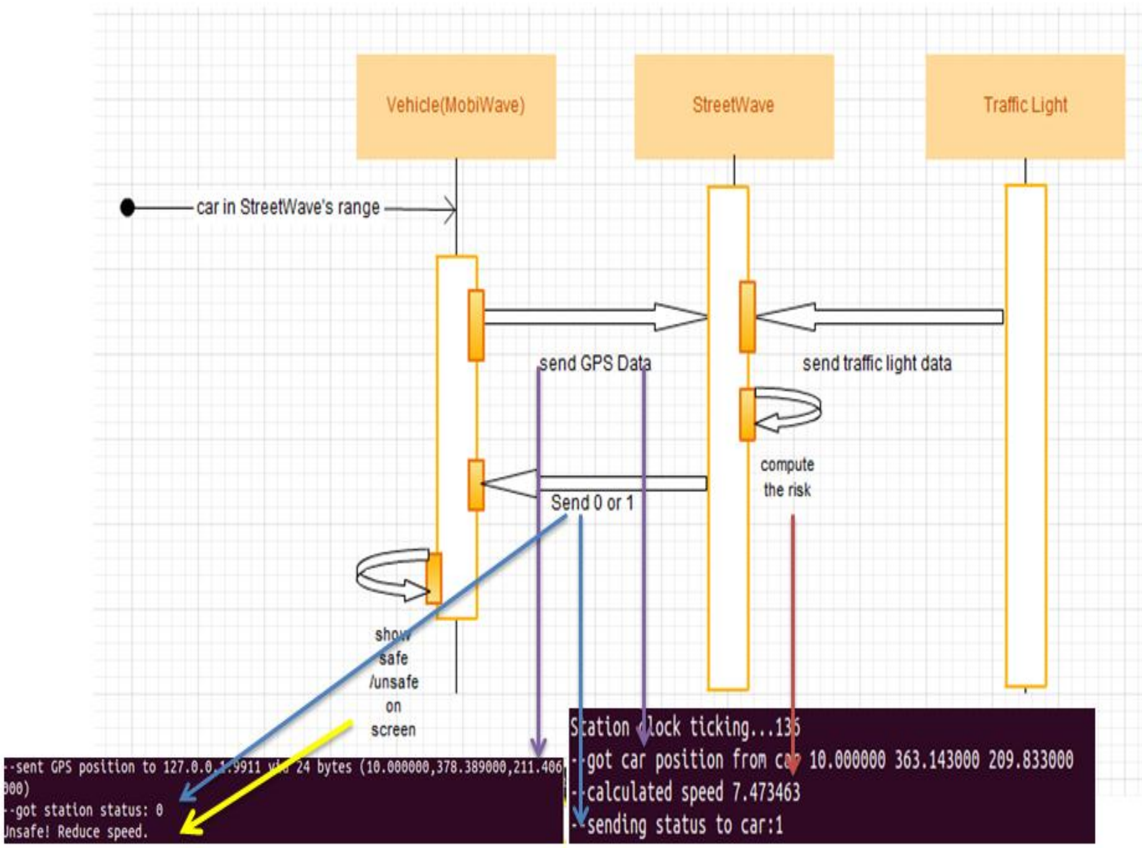


Figure 5.8 Order of events in decision assistance

Chapter 6 Summary and Conclusions

This research examined the effect of information on drivers approaching high-speed intersections. Data was collected at five intersections providing drivers with information via AWF; an additional site lacking AWF was also evaluated. The probit model was used to model driver decisions at the onset of yellow. The results were intended to inform conclusions on the effects of AWF on the probability of stopping and illustrate their influence on perceived conflict curves. Sites providing information through AWF curves displayed a tendency toward earlier probability of stopping curves; in particular, Highway 2 and US-75 probability of stopping curves differed drastically from the other studied sites. The shift at US-75 resulted in virtually all drivers approaching the intersection with the potential for minor or severe conflict. The risk associated with being downstream of the severe deceleration distance and upstream of the maximum passing distance was calculated for a variety of speeds at each intersection. An overall weighted average was then computed and compared to the crash histories. An association could be seen in the comparison between the crash histories and the computed risks, as sites with large severe deceleration risk had higher rear-end crash averages, and vice-versa. Therefore, it was evident that providing drivers with information in advance of the intersection using AWF could potentially increase the risk of rear-end accidents and RLR, as opposed to decreasing the risk for drivers approaching these intersections. The information provided to the driver on stop and go should be consistent with the actual duration of yellow. If the yellow time is longer and the driver is incorrectly asked to stop, the result is confusion that results in riskier intersections. It should also be noted that, when no information was provided, the critical time threshold for stopping was very close to the actual yellow duration. This implies that drivers were inclined to stop when the time to stop bar was greater than the yellow time, and were inclined to go when the time to stop bar was less than yellow time.

The YODA system was developed, harnessing the insights gained regarding the impact of information on driver decision making. The system consists of two units, MobiWave and StreetWave. MobiWave is an on-board-unit capable of providing wireless and wired communication systems. MobiWave sends the vehicle location information to StreetWave when it is within a detectable range. Upon receiving this information, StreetWave computes the risks for the vehicle, and sends back information on whether the vehicle can make it across the stop bar within the remaining yellow time if the vehicle continues to travel at its current speed. MobiWave displays this decision to the driver using a human machine interface.

6.1 Future Research

The future YODA system could incorporate the impacts of weather, time of day, volume conditions, and the presence of other vehicles. Such site-specific information would make the information provided to the driver more precise and case sensitive.

References

Akaike's Information Criterion. Accessed June 12, 2009. http://www.modelselection.org/aic/.

Archer, J. 2004. "Methods for the assessment and prediction of traffic safety at urban intersections and their application in micro-simulation modeling." Royal Institute of Technology, Department of Infrastructure, Stockholm, Sweden.

Armstrong, L. n.d. "Dedicated short range communications (DSRC) home." http://www.leearmstrong.com/Dsrc/DSRCHomeset.htm

Baker W. 1972. "An evaluation of the traffic conflict technique." *Highway Research Record*, 384: 1-8.

Bonneson, J., and K. Zimmerman. 2005. "In-service evaluation of a detection-control system for high-speed signalized intersections." *Report No. FHWA/TX-05/5-4022-01-1*, Texas Department of Transportation, Austin, TX.

Bonneson, J., K. Zimmerman, and M. Brewer. 2002. "Engineering countermeasures to reduce red-light running," *Report No. 4027-2*. Federal Highway Administration, Washington, D.C.

Bonneson, J.A. and J. H. Son. 2003. "Prediction of expected red-light running frequency at urban intersections." *Transportation Research Record*, 1830: 38-47.

Chang, M., C. Messer, and A. Santiago. 1985. "Timing traffic signal change intervals based on driver behavior." *Transportation Research Record*, 1027: 20-30.

Cooper, P. 1973. "Predicting intersection accidents." Ministry of Transport, Canada Road and Motor Vehicle Traffic Safety Branch.

Cooper, D., and N. Ferguson. 1976. "Traffic studies at T-junctions: A conflict simulation model." *Traffic Engineering and Control*, 17, pg. 306-309.

Econometric Software, Inc. 2007. *NLOGIT 4.0*. Plainview, NY: author.

Elmitiny, N., X. Yan, C. Russo, and D. Nashar. 2010. "Classification analysis of driver's stop/go decision and red light running violation." *Accident Analysis and Prevention*, 42, no. 1: 101-111.

Farraher, B. A., B. R. Wenholzer, and M. P. Kowski. 1999. "The effect of advance warning flashers on red-light-running-A study using motion imaging recording system technology at trunk highway 169 and Pioneer Trail in Bloomington, Minnesota." *Presented at the 69th Annual Meeting of ITE,* Las Vegas, Nevada.

Fazio, J., J. Holden, and N. Rouphail. 1993. "Use of freeway conflict rates as an alternative to crash rates in weaving section safety analysis." *Transportation Research Record*, 1401: 61-69.

Gates, T. J., D. A. Noyce, L. Laracuente, and G. Davis. 2006. "Effect of yellow-phase trigger on driver's behavior at high-speed signalized intersections." *Proceedings of 2006 IEEE Conference on Intelligent Transportation Systems*. Toronto, Canada, 683-688.

Gazis, D., R. Herman, and A. Maradudin. 1960. "The problem of amber signal light in traffic flow." *Operations Research*, 8, no. 1: 112-132.

Gettman, D. and L. Head. 2003. "Surrogate safety measures from traffic simulation models." *Report No. FHWA-RD-03-050*, Federal Highway Adninistration, U.S. Department of Transportation, Washington D.C.

Gettman, D., L. Pu, T. Sayed, and S. Shelby. 2008. "Surrogate safety assessment model and validation: Final report." *Publication No. FHWA-HRT-08-051*. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Gibby, A.R., S.P. Washington, and T.C. Ferrara. 1992. "Evaluation of high-speed isolated signalized intersections in California." *Transportation Research Record*, 1376: 45-56.

Glauz, W., K. Bauer, and D. Migletz. 1985. "Expected traffic conflict rates and their use in predicting accidents." *Transportation Research Record*, 1026: 1-12.

Glennon J., W. Glauz, M. Sharp, and B. Thorson. 1977. "Critique of the traffic-conflict technique." *Transportation Research Record*, 1026: 1-12.

Grayson, G. B. 1984. "The Malmo Study: A calibration of Traffic Conflict Techniques," *Report R-84-12*, Institute for Road Safety Research SWOV, Leidschendam, Netherlands.

Hakkert, A. S., and D. Mahalel. 1978. "The effect of traffic signals on road accidents with special reference on the introduction of a blinking green phase." *Traffic Engineering & Control*, 19: 212-215.

Hauer, E., and P. Garder. 1986. "Research into the validity of the traffic conflict techniques." *Accident Analysis & Prevention*, 18: 471-481.

Hayward, J. 1972. "Near miss determination through use of a scale of danger." *Report no. TTSC 7715*, Pennsylvania State University, PA.

Herman, R., P. L. Olson, and R.W. Rothery. 1963. "Problem of the amber signal light." *Traffic Engineering and Control*, 5: 298-304.

Hocherman, I., and J. Prashker. 1983. "Identification of high risk intersections in urban areas." *Paper presented at the 1983 Annual Meeting of the PTRC*, Brighton, U.K.

Hurwit, D. 2009. “Application of driver behavior and comprehension to dilemma zone definition and evaluation.” Ph.D. diss., University of Massachusetts, Amherst, MA.

Hyden, C. 1987. “The development of a method for traffic safety evaluation: The Swedish traffic conflicts technique.” *Bulletin 70,* University of Lund, Lund Institute of Technology, Lund, Sweden.

ITE technical committee 18, (P. Parsonson, Chairman). 1974. “Small-area detection at intersection approaches.” *Traffic Engineering*, February 1974, Institute of Transportation Engineers, Washington D.C., 8-17.

Kim, W., J. Zhang, A. Fujiwara, T. Y. Jang, and N. Moon. 2008. “Analysis of stopping behavior at urban signalized intersections.” *Transportation Research Record,* 2080: 84-91.

Knodler Jr., M. A., and D. Hurwitz. 2009. “An evaluation of dilemma zone protection practices for signalized intersection control.” *Report No. 2009-6*, University of Massachusetts Transportation Center, Amherst, MA, Vermont Agency of Transportation, Montpelier, VT.

Koll, H., M. Bader, and K.W. Axhausen. 2004. “Driver behaviour during flashing green before amber: A comparative study.” *Accident Analysis & Prevention,* 36: 273-280.

Kraay, J. H., & A. R. A. van der Horst. 1985. “Trautenfels-study: A diagnosis of road safety using the Dutch Conflict observation technique DOCTOR.” *Report R-85-53*, Institute for Road Safety Research SWOV, Leidschendam, Netherlands.

Kronborg, P., and F. Davidson. 1993. “MOVA and LHOVRA: Traffic signal control for isolated intersections.” *Traffic Engineering and Control*, 34, no. 4: 193-200.

Kronborg, P., F. Davidsson, and J. Edholm. 1997. “Development and field trials of the SOS algorithm for self optimising signal control at isolated intersections.” *Publication TFK - 1997-05-07*. Transportation Research Institute, Stockholm, Sweden.

Li, P. 2009. “Stochastic methods for dilemma zone protection at signalized intersections.” Virginia Tech University, Blacksburg, VA.

Liu, Y., G. –L. Chang, R. Tao, T. Hicks, and E. Tabacek. 2006. “Empirical observations of dynamic dilemma zones at signalized intersections.” *Transportation Research Record,* 2035: 122-133.

Liu, C., R. Herman, and D. Gazis. 1996. “Review of the yellow interval dilemma.” *Transportation Research Part A,* 30: 333-348.

Mahalel, D. and J. N. Prashker. 1987. “A behavioral approach to risk estimation of rear-end collisions at signlized intersections.” *Transportation Research Record,* 1114: 96-102.

Mahalel, D., and D. M. Zaidel. 1985. "Safety evaluation of a flashing-green light in a traffic signal." *Traffic Engineering Control*, 26: 79-81.

Mahalel, D., D. M. Zaidel, and T. Klein. 1985. "Driver's decision process on termination of the green light." *Accident Analysis & Prevention*, 17: 373-380.

Mahmassani, S., and A. Probit. 1979. "Model of driver behavior at high speed isolated signalized Intersections." *C.S. Working Paper No. 79-10*, Massachusetts Institute of Technology.

Malkhamah, S., M. Tight, and F. Montgomery. 2005. "The development of an automatic method of safety monitoring at Pelican crossings" *Accident Analysis and Prevention*, 37: 938-946.

May A. D. 1968. "Clearance interval at flashing systems." *Highway Research Record*, 221: 41-71.

Messer, C. J., S. R. Sunkari, H. A. Charara, and R. T. Parker. 2003. "Development of advance warning systems for end-of-green phase at high speed traffic signal.*" Report 4260-4*, Federal Highway Administration, Washington, D.C., Texas Department of Transportation, Texas Transportation Institute, Texas A & M University System.

Middleton, D., D. Jasek, H. Charara, and D. Mors. 1997. "Evaluation of innovative methods to reduce stops to trucks at isolated signalized intersections." *Report No. TX-97/2972-S*, Texas Transportation Institute, Texas A&M University System.

Minderhoud, M. and P. Boy. 2001. "Extended time-to-collision measures for road traffic safety assessment." *Accident Analysis & Prevention*, 33: 89-97.

National Highway Traffic Safety Administration. 2007. *Traffic Safety Facts 2006.* Washington D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Nebraska Department of Roads. 1999. *Traffic crash facts 1998.* Lincoln, NE: author.

Nebraska Department of Roads. 2000. *Traffic crash facts 1999.* Lincoln, NE: author.

Nebraska Department of Roads. 2001. *Traffic crash facts 2001.* Lincoln, NE: author.

Nebraska Department of Roads. 2002. *Traffic crash facts 2002.* Lincoln, NE: author.

Nebraska Department of Roads. 2003. *Traffic crash facts 2003.* Lincoln, NE: author.

Nebraska Department of Roads. 2004. *Traffic crash facts 2004.* Lincoln, NE: author.

Nebraska Department of Roads. 2005. *Traffic crash facts 2005.* Lincoln, NE: author.

Nebraska Department of Roads. 2006. *Traffic crash facts 2006.* Lincoln, NE: author.

Nebraska Department of Roads. 2007. *Traffic crash facts 2007.* Lincoln, NE: author.

Nebraska Department of Roads. 2008. *Traffic crash facts 2008*. Lincoln, NE: author.

Nebraska Department of Roads. 2009. *Traffic crash facts 2009*. Lincoln, NE: author.

Newton, C., R. Mussa, E. Sadalla, E. Burns, and J. Matthias. 1997. "Evaluation of an alternative traffic light change anticipation system." *Accident Analysis and Prevention*, 29, no. 2: 201-209.

Olson, P., and R. Rothery. 1962. "Driver response to amber phase of traffic signals." *Highway Research Board*, 330: 40-51.

Paddock, R. 1974. "The traffic conflict technique: An accident prediction method." Ohio Department of Transportation, Division of Highways, Bureau of Traffic Control.

Pant, P. D., and X. H. Huang. 1992. "Active advance warning signs at high-speed signalized intersections: Results of a study in Ohio." *Transportation Research Record,* 1368: 18-26.

Pant, P. D., and Y. Xie. 1995. "Comparative study of advance warning signs at high-speed signalized intersections." *Transportation Research Record*, 1495: 28-35.

Papaioannou, P. 2007. "Driver behavior, dilemma zone and safety effects at urban signalised intersections in Greece." *Accident Analysis and Prevention*, 30, no. 1: 147-158.

Parsonson, P. 1978. "Signalization of high speed, isolated intersections." *Transportation Research Record*, 681: 34-42.

Parsonson, P. S., and A. Santiago. 1980. "Design standards for timing-The traffic signal clearance period must be improved to avoid liability." *Compendium of Technical Papers, 1980 ITE Conference*, 67-71.

Perkins, S. R., and J. I. Harris. 1968. "Traffic conflict characteristics: Accident potential at intersections." *Highway Research Record*, 225: 45-143.

Rakha, H., I. El-Shawarby, and J. R. Setti. 2007. "Characterizing driver's behavior on signalized intersection approaches at the onset of a yellow-phase trigger." *IEEE Transactions on Intelligent Transportation System*, 8, no. 4: 630-640.

Research and Innovative Technology Administration (RITA) • U.S. Department of Transportation (US DOT), http://www.rita.dot.gov/

Savari. n.d. www.Savarinetworks.com.

Sayed, T, V. Homoyaoun, and F. Rodriquez. 1999. “Advance warning flashers, do they improve safety?” *Transportation Research Record*, 1692: 30-38.

Sharma, A. 2008. “Integrated behavioral and economic framework for improving dilemma zone protection systems.” Ph.D. diss., Purdue University.

Sharma, A., D. Bullock and S. Peeta. 2011. “Estimating dilemma zone hazard function at high speed isolated intersection.” *Transportation Research Part C: Emerging Technologies*, 19, no. 3: 400-412.

Sharma, A., D. Bullock, and S. Peeta. 2007. “Recasting dilemma zone design as a marginal costs-benefits problem.” *Transportation Research Record*, 2035: 88-96.

Sharma, A., M. Harding, B. Giles, D. Bullock, J. Sturdevant, and S. Peeta. 2008. “Performance requirement and evaluation procedures for advance wide area detector.” *Paper presented at the 87th Annual Meeting of the Transportation Research Board*, Washington, D.C.

Sheffi, Y., and M. Mahmassani. 1981. “A model of driver behavior at high speed signalized intersections.” *Transportation Science*, 15, no. 1: 51-61.

Sivak, M., P. L. Olson, and K. M. Farmer. 1982. “Radar measured reaction times of unalerted drivers to brake signals.” *Perceptual and Motor Skills*, 55: 594.

Spicer, B. A. 1972. “A traffic conflict study at an intersection on the Andoversford by-pass.” *TRRL Report LR 520*, Transport and Road Research Laboratory, Road User Characteristics Division, Safety Department.

Stander, H. J. 1989. “Timing of the change interval at traffic signals.” Presented at the *Annual Transportation Convention*, Pretoria, South Africa.

Van der Horst, A. R. A. 1984. “The ICTCT calibration study at Malmo: a quantitative analysis of video-recordings.” *Report IZF 1984-37*, TNO Institute for Perception, Soesterberg, Netherlands.

Van der Horst, A. R. A. 1990. “A time-based analysis or road user behaviour in normal and critical encounters.” Ph.D. diss., Delft University of Technology, Delft, Netherlands.

Van der Horst, R. and A. Wilmink, 1986, “Driver’s Decision-Making at Signalized Intersections: An Optimization of the Yellow Timing,” *Traffic Engineering & Control*. pp. 615-622.

Wavetronix. 2009. “SmartSensor Advance.” www.wavetronix.com/en/products/smartsensor/advance/safearrival. Accessed February 9, 2011.

Wei, H., Z. Li, and Q. Ai. 2009. “Observation-based study of intersection dilemma zone natures.” *Journal of Transportation Safety & Security*, 1, no. 4: 282-295.

Williams, W. L. 1977. “Driver behavior during yellow interval.” *Transportation Research Record*, 644: 75-78.

Wortman, R. H., and J. S. Matthias. 1983. “Evaluation of driver behavior at signalized intersections.” *Transportation Research Record*, 904: 10-20.

Xsens Technologies B.V. 2009. *MTi-G Quick setup: Getting started with your MTi-G* (p. 4). Enschede, Netherlands: author.

Zeeger, C., 1977. “Effectiveness of green-extension systems at high-speed intersection.” *Research Report 472*, Bureau of Highways, Kentucky Department of Transportation, Lexington, Kentucky.

Zimmerman, K. 2007. “Development of a second generation detection-control system for safer operation of high-speed signalized intersections.” *Report No. TRB-NCHRP-115*, Texas Transportation Institute, Texas A&M University System.